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STUDY OF ADHESION AND COHESION IN VACUUM

20 AUGUST 1965

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CULVER CITY CALIFORNIA

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AEROSPACE GROUP
MATERIALS TECHNOLOGY DEPARTMENT
Culver City, California

STUDY OF ADHESION AND COHESION IN VACUUM

by

P. M. Winslow
D. V. McIntyre

20 August 1965

Final Report

Contract Number NAS 8-11066
Control Number 223-85487(1F)
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George C. Marshall Space Flight Center
Huntsville, Alabama

Approved: [signature]
W. H. Colner, Manager
Materials Technology Department

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FOREWORD

This report was prepared by the Hughes Aircraft Co. under Contract No. NAS 8-11066, "An Investigation of Adhesion and Cohesion in Vacuum", for the George C. Marshall Space Flight Center of the National Aeronautics and Space Administration. The work was administered under the technical direction of the Propulsion and Vehicle Engineering Laboratory, Materials Division of the George C. Marshall Space Flight Center, with Mr. Keith Demorest acting as project manager. Mr. P. M. Winslow was the contractor's project engineer.

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I. ABSTRACT

This study was made to determine the temperature, time and conditions under which adhesion or cohesion of structural metals occurs in a vacuum. The objective was to provide spacecraft designers with engineering data to ensure separation of instrument capsules and other components from spacecraft in the space environment.

These studies were conducted at an environmental pressure of 5×10^{-9} torr over a temperature range of 25C (77F) to 500C (932F) and at compressive stresses within the elastic limits of the materials. Surface finishes and cleanliness of the test specimens simulated those of spacecraft hardware. Static tests in continuation of the prior year's testing program were made and the adhesive forces were measured. In these tests, only copper to copper and couples containing 2014 aluminum bonded. None of these couples bonded at 150C, but they generally bonded at 300C. These couples were: (1) copper to copper, (2) 2014 aluminum to 2014 aluminum, (3) 2014 aluminum to 304 steel, (4) 2014 aluminum to A 286 steel, (5) 2014 aluminum to René 41 alloy and (6) 2014 aluminum to 6Al-4V-titanium alloy.

The equipment was modified for conducting dynamic tests in which one of the test specimens was oscillated ± 2 degrees at 3 cps against the other (stationary) test specimen while under compressive load. Tests made with eleven material combinations established conditions of adhesion and cohesion. As was anticipated, adhesion and cohesion occurred more readily than in the static tests. All material combinations adhered or cohered under test conditions within the prescribed parameters. Like metal couples bonded more readily than unlike metal couples. The reason for this may be that higher shear forces existing at the bond interface of dissimilar metal couples may rupture the bond.

The following material combinations bonded when tested at room temperatures: (1) A 286 steel to A 286 steel, (2) 304 steel to 304 steel, (3) René 41 alloy to René 41 alloy, (4) 6Al-4V-titanium alloy to 6Al-4V-titanium alloy, and (5) copper to copper.

Author

The remainder of the couples did not bond at room temperature, but did bond at 150C. These couples were: (1) 2014 aluminum to 2014 aluminum, (2) 304 steel to 2014 aluminum, (3) 304 steel to René 41 alloy, (4) 2014 aluminum to René 41, (5) 2014 aluminum to A 286 steel, and (6) 2014 aluminum to 6Al-4V-titanium alloy.

From these tests, it is concluded that the natural barrier films that impede intimate metal to metal contact are effective in preventing adhesion or cohesion in static loading of the harder materials such as stainless steels, super-alloys, and titanium alloys. This mechanism also seems to be effective in avoiding bonding of the softer materials such as copper and aluminum alloys at temperatures up to 150C. Their tendency to bond at 300C may be due to diffusion of their oxide films into the metals at the higher temperature.

The relative ease with which the couples bonded in the dynamic tests clearly demonstrates how the mechanical abrasion in denuding the surfaces of their barrier films, promotes bonding.

II. DEFINITION OF TERMS

In normal usage, adhesion is defined as the molecular attraction exerted between the surfaces of separate bodies in contact. Cohesion is defined as the molecular attraction by which particles of a single body are united throughout the mass, whether the particles are like or unlike. From these definitions, it would appear that the tests conducted in this study, where separate bodies are brought into contact, would all be classified as adhesion tests. However, if two specimens of the same material are brought into contact and they bond to each other, they in effect become one body. With a broad license this might be termed cohesion.

In this report, because of the contractual semantics, bonding of like materials is termed cohesion, while bonding of unlike materials is termed adhesion.

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III. INTRODUCTION

The purpose of this program was to determine the temperature, time, and conditions under which adhesion or cohesion of metals in a vacuum occurs. The results of this study will provide spacecraft designers with engineering data required to insure that instrument capsules and other removeable components may be separated from the spacecraft in the space environment.

Accomplishments of the first year's program included the design and fabrication of a vacuum test chamber incorporating the following features: (1) an environmental pressure of less than 5×10^{-9} torr, (2) a static loading device capable of applying and measuring tensile and compressive forces of from 0 to 100,000 psi, and (3) a range of testing temperatures from 25C to 500C. Tests were made by applying compressive loads for given time periods, to two contacting test specimens in the vacuum chamber. The tensile force required to separate the two test specimens was then measured in the vacuum to determine the extent of adhesion or cohesion. Thirteen different combinations of metal couples were evaluated. Material screening tests were performed first under the most severe environmental conditions of contact pressure and temperature. Material combinations that bonded under the most severe conditions were then tested at the next lower specified temperature to determine the threshold conditions at which bonding failed to occur. This test philosophy is based on the assumption that if materials loaded to a specified load do not bond at a given temperature, they likewise will not bond at lower temperatures in similar time periods.

The second year's program, reported herein, continued the work of the first year. However, in addition to the static loading tests, dynamic tests were performed in which oscillatory motion was applied to one of the test specimens while under a compressive load. This required modification of the test apparatus to provide the oscillatory motion of ±2 to 5 degrees at 1 to 100 cps. Eleven test couples were studied in this mode, and time, temperature, and loads at which adhesion or cohesion occurred were determined.

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IV. WORK ACCOMPLISHED PRIOR TO CURRENT REPORTING PERIOD

Results obtained during the first year's study and reported in Reference 1, are summarized below.

Thirteen material combinations were studied and eight of these did not bond under test conditions of maximum severity. These conditions, established as criteria for adhesion and cohesion, were to load the test specimens to 80 percent of their compressive yield strengths or a load at which creep would not occur in 70,000 seconds. The environmental pressure was held at 5×10^{-9} torr. Under these conditions, the following eight materials did not bond at 500C: (1) 304 steel to 304 steel, (2) 304 steel to A 286 steel, (3) 304 steel to Rene' 41 alloy, (4) A 286 steel to A 286 steel, (5) Rene' 41 alloy to Rene' 41 alloy, (6) 6Al-4V-titanium alloy to Rene' 41 alloy and (7) A 286 steel to Rene' 41 alloy. No. (8), the 6Al-4V-titanium alloy did not bond to itself at 500C, but its creep strength was exceeded.

Copper bonded to itself at temperatures as low as 300C. The 2014 aluminum alloy showed a tendency to bond to itself and to other alloys at 300C. Because the elastic limit of the aluminum alloy was exceeded with a number of those couples, their minimum threshold of adhesion and cohesion was not established.

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V. TEST EQUIPMENT

Test equipment used in the experimental program consisted of the vacuum system developed in the first year's program together with a number of modifications required to perform the dynamic testing. The equipment and modifications are described below.

VACUUM SYSTEM

The basic features of the vacuum system are fully described in Reference 1 and summarized below.

This system employs sorption fore-pumping to avoid roughing pump oil contamination. A 100-liter per second Ultek sputter ion pump and power supply are used to maintain the ultra high vacuum.

The vacuum system for static tests had maintained pressures as low as 2×10^{-9} torr despite the gas load imposed by specimens heated to 500C. However, for the dynamic tests, it was anticipated that even higher gas loads would be introduced into the modified system because of oscillatory motion. In addition, the heating of some specimen materials (e.g., Ti-6Al-4V) had previously caused so much outgassing that the existing system could not achieve the desired pressure of 5×10^{-9} torr. Therefore, to increase the system pumping speed, a titanium sublimation pump was added. It was connected between the working chamber and the 100 liter/sec ion-pump.

The 304 stainless steel body of this pump is shown in Figure 1. Through the small flanged opening on the side of the body, a titanium filament holder (Ultek 10-470) was inserted. This filament holder is electrically connected to a power supply (Ultek 60-655) which operates both the titanium sublimation pump and the 100 liter/sec ion-pump. When a current of 38 amps flows through the titanium filament, the titanium is heated and sublimes onto the wall of the pump body. The baffle shown in Figure 1 prevents titanium from directly entering the test chamber containing the specimens. This film of freshly sublimed titanium does the actual pumping, with a typical pumping speed of about 15 liters/sec for each square inch of deposited titanium. The net effective pumping speed, as determined by the conductance of the upper flanged opening, is 670 liters/sec.

The power supply is equipped with a timer which turns on the current to sublime titanium at predetermined time intervals. The titanium sublimation rate can be varied to achieve the desired pumping speeds for the different gas loads imposed by each specimen-temperature combination.

Copper tubing, silver brazed to the outside of the pump body, provides water cooling for the pump. The chamber was electropolished to decrease gas adsorption on the walls.

Pressures in the static-test vacuum-chamber were determined in all previous tests by measuring the pump ion-current. Since installation of the sublimation pump located the ion-pump further from the vacuum chamber, a vacuum gauge was installed. The pressure measurements in the modified chamber are made by a Kreisman type

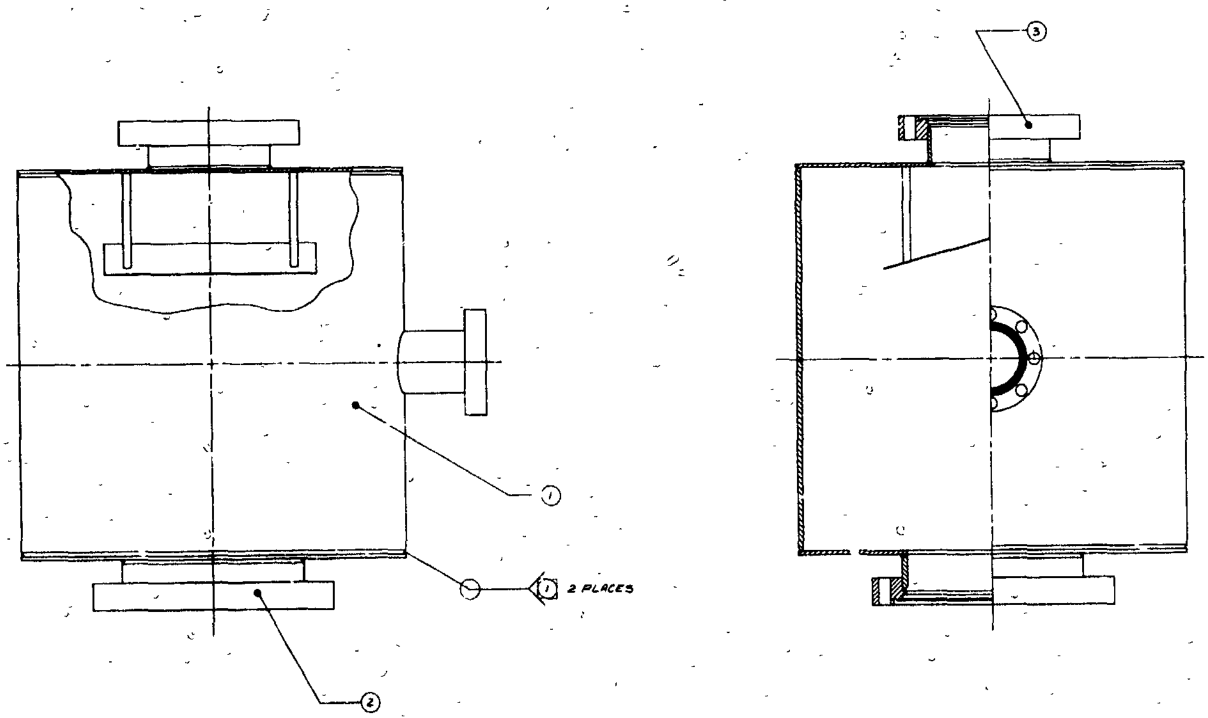


Figure 1. Titanium sublimation pump assembly.

of cold-cathode discharge gauge (Vactek 1410) which operates from 10^{-4} to 10^{-14} torr. This bakeable gauge is mounted on a 2-3/4 inch flange which allows it to be connected directly to the vacuum chamber containing the specimens. Measurements made in this nearer location more truly represent the vacuum at the specimens that would measurements made by a remotely located gauge. The gauge is operated by a special line-regulated and load-regulated power supply (Vactek 1400).

After a thorough bakeout and operation of the titanium sublimation pump in conjunction with the ion pump, a pressure of 2×10^{-10} torr has been registered on the Kreisman gauge at ambient temperature.

Although the titanium sublimation pump had a pumping speed of 670 liters per second, this speed could not be utilized because of low conductance (or a restriction) of the opening existing in the base plate of the old apparatus. Due to this limitation, its full potential was not realized.

DYNAMIC TESTING

The design modification for imparting oscillatory motion to the test specimens made use of much of the original static test equipment described in Reference 1 and shown in Figure 2.

Axial loads were applied by a double acting hydraulic ram connected to the upper flange and movable specimen through a strain link. The hydraulic ram was used for dynamic loading. A lever arm for dead weight loading was substituted for the ram for static loading. The strain link was equipped with semi-conductor strain gages which enabled accurate measurements at both extremely low and high loads. The output-load characteristics of the strain link are shown in Appendix A. The applied axial loads and separating forces were measured and recorded on a Varian G-11A recorder. The recorder has a 10 millivolt full scale deflection on 5-inch chart paper and a response of 0.1 second per millivolt.

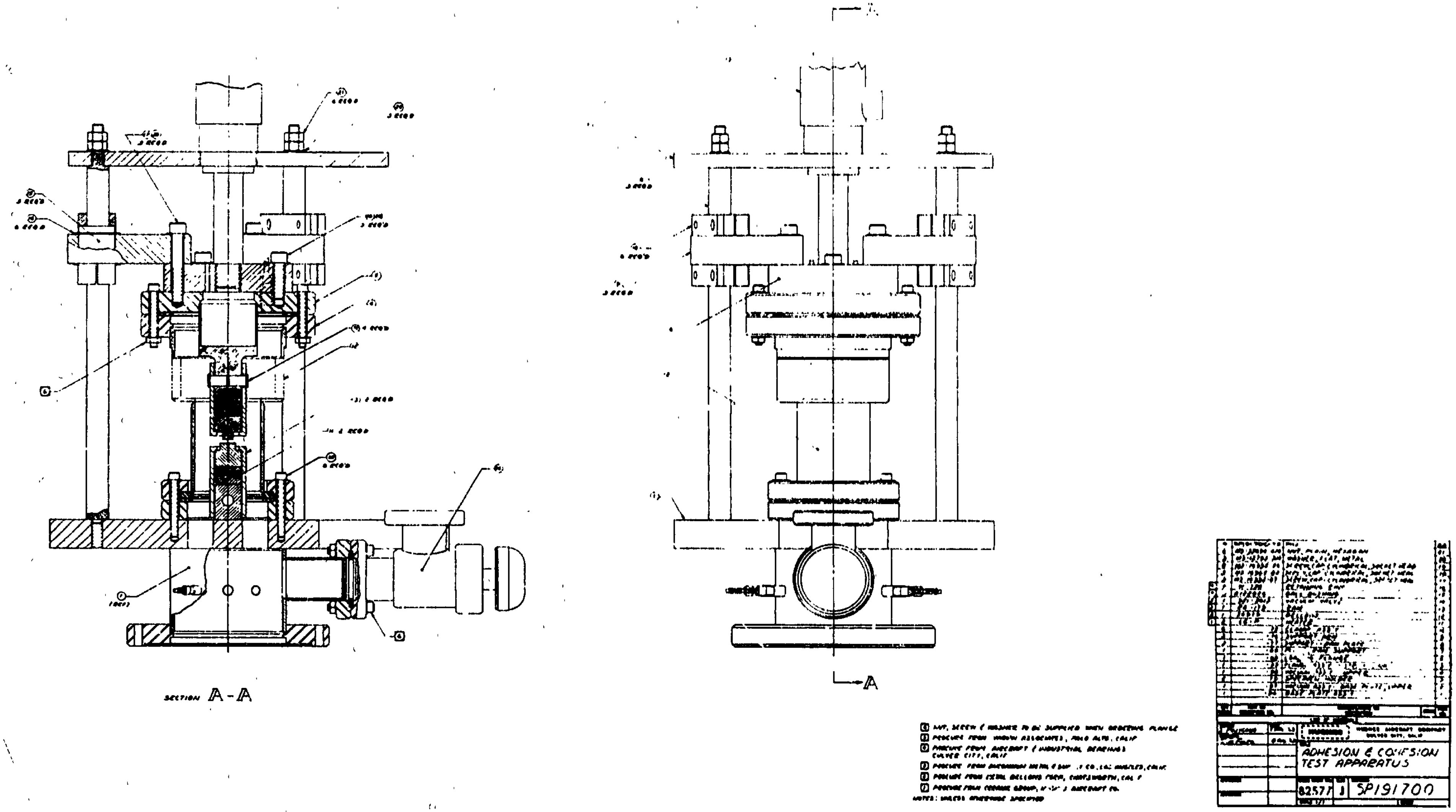


Figure 2. Static adhesion and cohesion test apparatus.

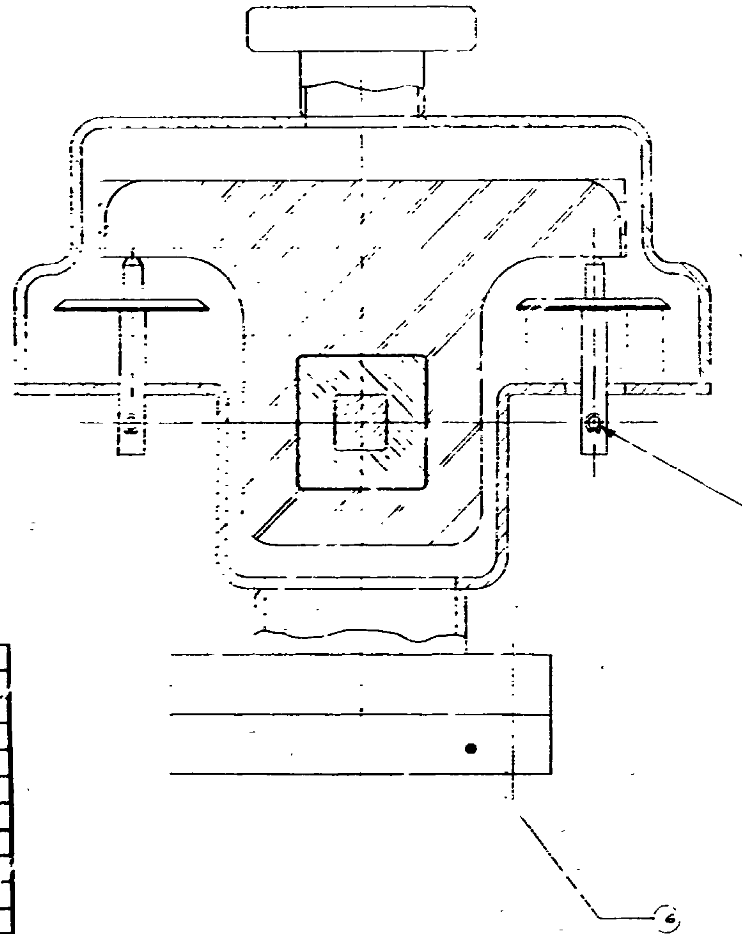
In modifying the static test apparatus to incorporate dynamic motion, the vacuum chamber assembly located between the lower base plate assembly (item 1) and the loading flange (item 6) of Figure 2 were replaced by a new vacuum chamber.

Features of the dynamic test apparatus are shown in Figure 3. The vacuum chamber assembly consists of a welded austenitic stainless steel housing of a shape to enclose the hub and fit the space available in the existing apparatus. This chamber, the hub assembly, the upper specimen holder, and the upper specimen move vertically as a unit to bring the test specimens in contact. A bellows located below the vacuum chamber assembly accommodates this motion. A viewing port and the Kreisman gauge are also incorporated into the vacuum chamber.

Sub-assemblies of the vacuum chamber were electropolished to improve the surface finish and minimize gaseous adsorption on the interior surfaces. Electropolishing the completed assembly was avoided because it was not possible to mask the metal bellows and there was danger of the chemical attack penetrating the thin walls.

The completed vacuum chamber is shown in Figure 4.

In operation the lower specimen remains stationary while the upper specimen is rotated ±2 degrees. The drive mechanism for transmitting rotary motion to the hub assembly consists of a direct drive motor with a gear reducer attached to the base plate and located outside of the test chamber. The hub assembly is rotated by two drive rods driving in opposite directions as shown in the schematic of Figure 5. Movement of the drive rods is transmitted into the vacuum chamber assembly by individual bellows welded to each shaft. The drive rods are pinned to shafts which are attached to the hub. These pin joints are located on the same center line as the test specimens. Thus, motion is imparted along tangents to a circle having its center at the center of the test specimen. This arrangement avoids joints inside the vacuum chamber with their attendant problems and permits the bellows



SECTION A - A

	QTY REQD	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	ZONE	ITEM NO.
4	4	5100-12	RETAINING RING		19
	1	-81	SPECIMEN--UPPER		18
	1	-80	SPECIMEN--LOWER		17
3	1	247002-067	VIEWING FLANGE		16
	3	-77	SUPPORT ROD EXTENSION		15
	2	-78	DRIVE ROD		14
	2	-74	DOWEL PIN		13
2	2	LG-P	HEATER		12
	1	-92	INSULATOR		11
	3	-93	INSULATOR DISC		10
	1	-94	SPECIMEN HOLDER--LOWER		9
	1	-95	SPECIMEN HOLDER--UPPER		8
	1	SP191700-99	FLANGE ASSY--STRAIN LINK		7
	4	SP191700-73	PIN		6
	1	-96	VACUUM CHAMBER ASSY--UPPER		5
	1	-97	VACUUM CHAMBER HUB ASSY		4
1	1	50511	BELLOWS		3
	1	SP205941-95	VACUUM ASSY--LOWER		2
	1	SP191700-96	BASE PLATE ASSY		1

LIST OF MATERIALS

DRAWN S. FOLKERTH	DATE 28 SEPT '64	HUGHES	HUGHES AIRCRAFT COMPANY CULVER CITY, CALIF.
CHECKED J GARVEY	12 OCT 64	TITLE ADHESION-COHESION--DYNAMIC TEST APPARATUS	
APPROVED		CODE IDENT NO. 82577	SIZE J NUMBER SP205941
APPROVED		SCALE NONE	SHEET 1 OF 26

4 PROCURE FROM WALDES KOHINOOR INC., LONG ISLAND CITY, N.Y.

3 PROCURE FROM GRANVILLE-PHILLIPS CO., BOULDER, COLO.

2 PROCURE FROM CERAMIC GROUP, HUGHES AIRCRAFT CO.

1 PROCURE FROM METAL BELLOWS CORP., CHATSWORTH, CALIF.

NOTES: U.O.S.

Figure 3. Adhesion-cohesion dynamic test apparatus.

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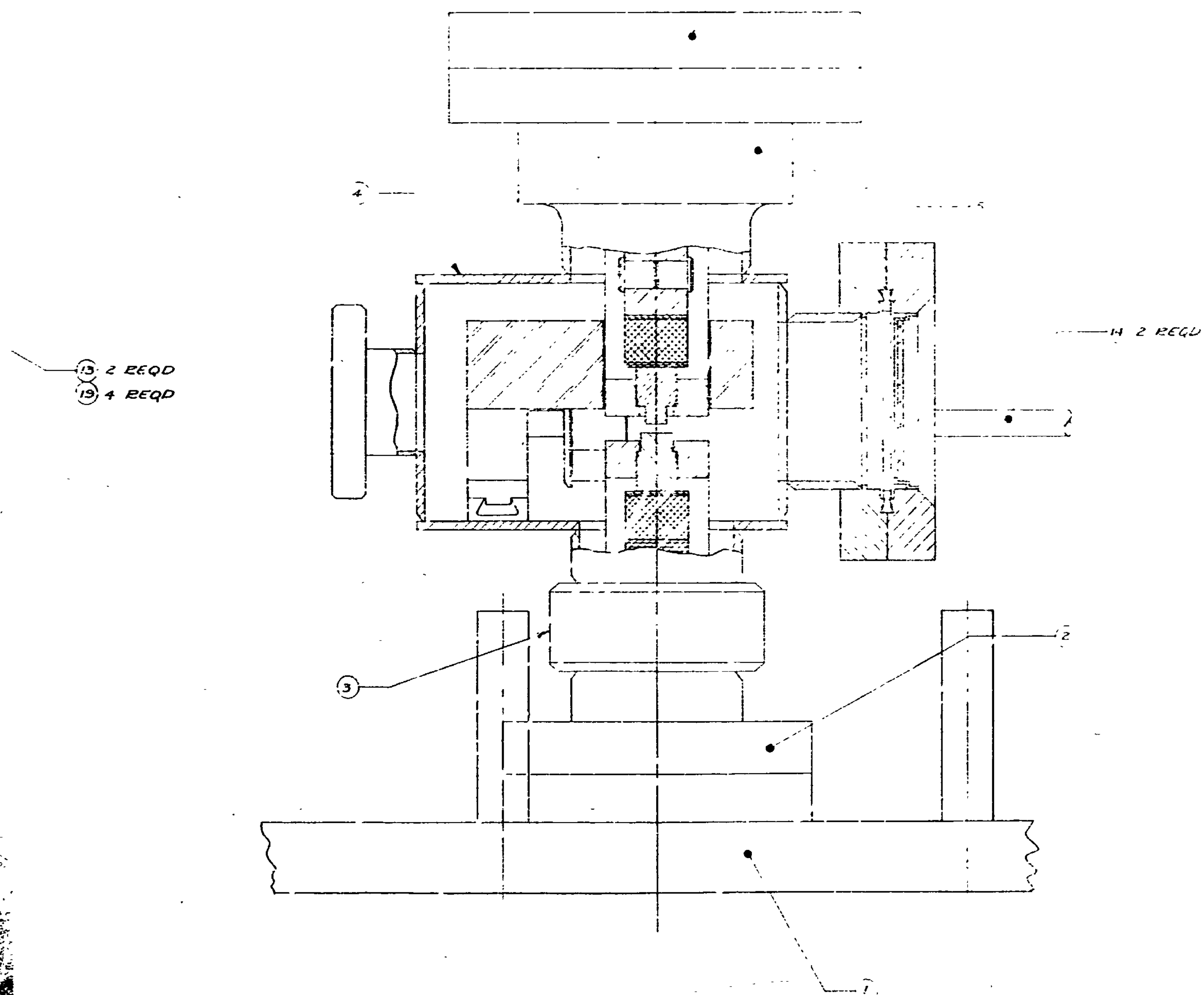

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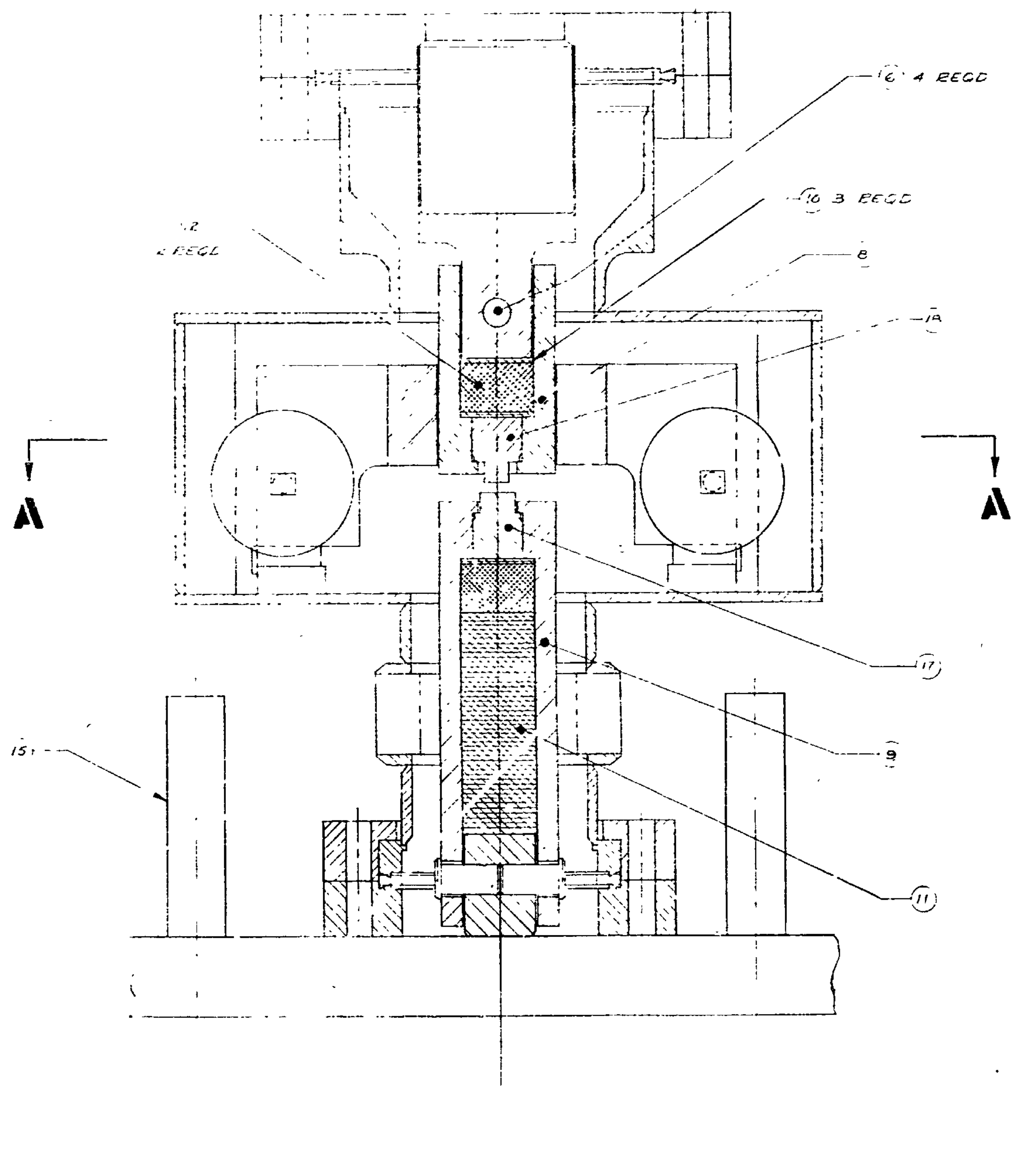
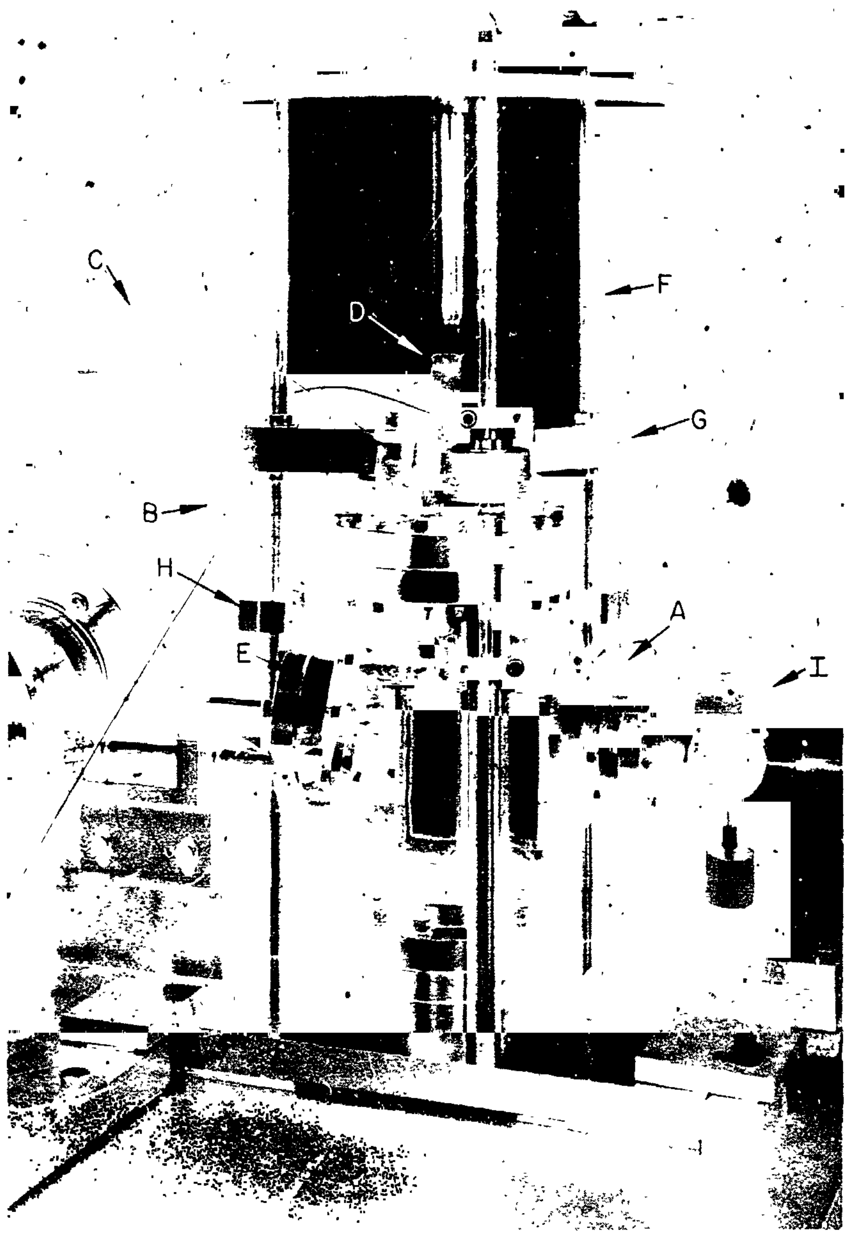
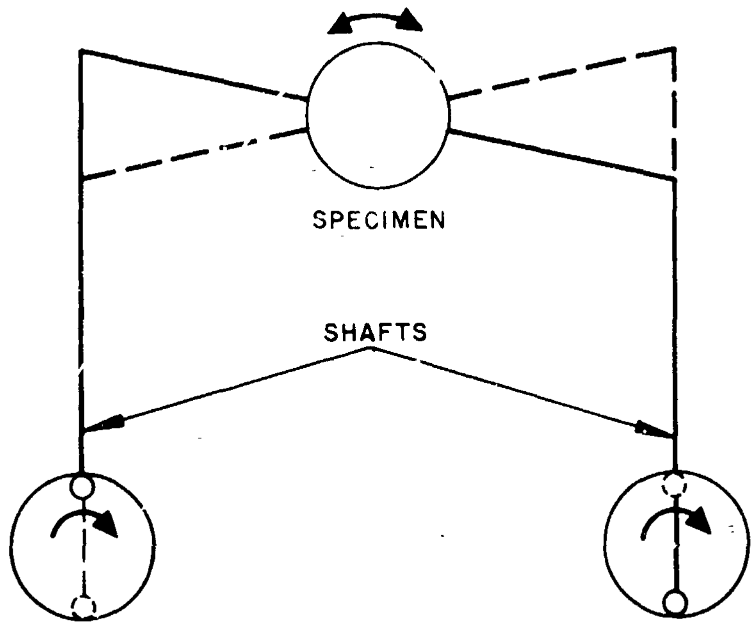




A. Vacuum Chamber
B. Heater Leads for Upper Specimen
C. Strain Gage Leads
D. Strain Link
E. Viewing Port
F. Guide Rod
G. Bearing Support Arm
H. Stop for Holding Specimens Apart
I. Kreisman Gage

Figure 4. Vacuum chamber assembly. (Negative No. R103424)



A. CAMS OFFSET – ROTATION

Figure 5. Kinemat s of rotation of test specimen.

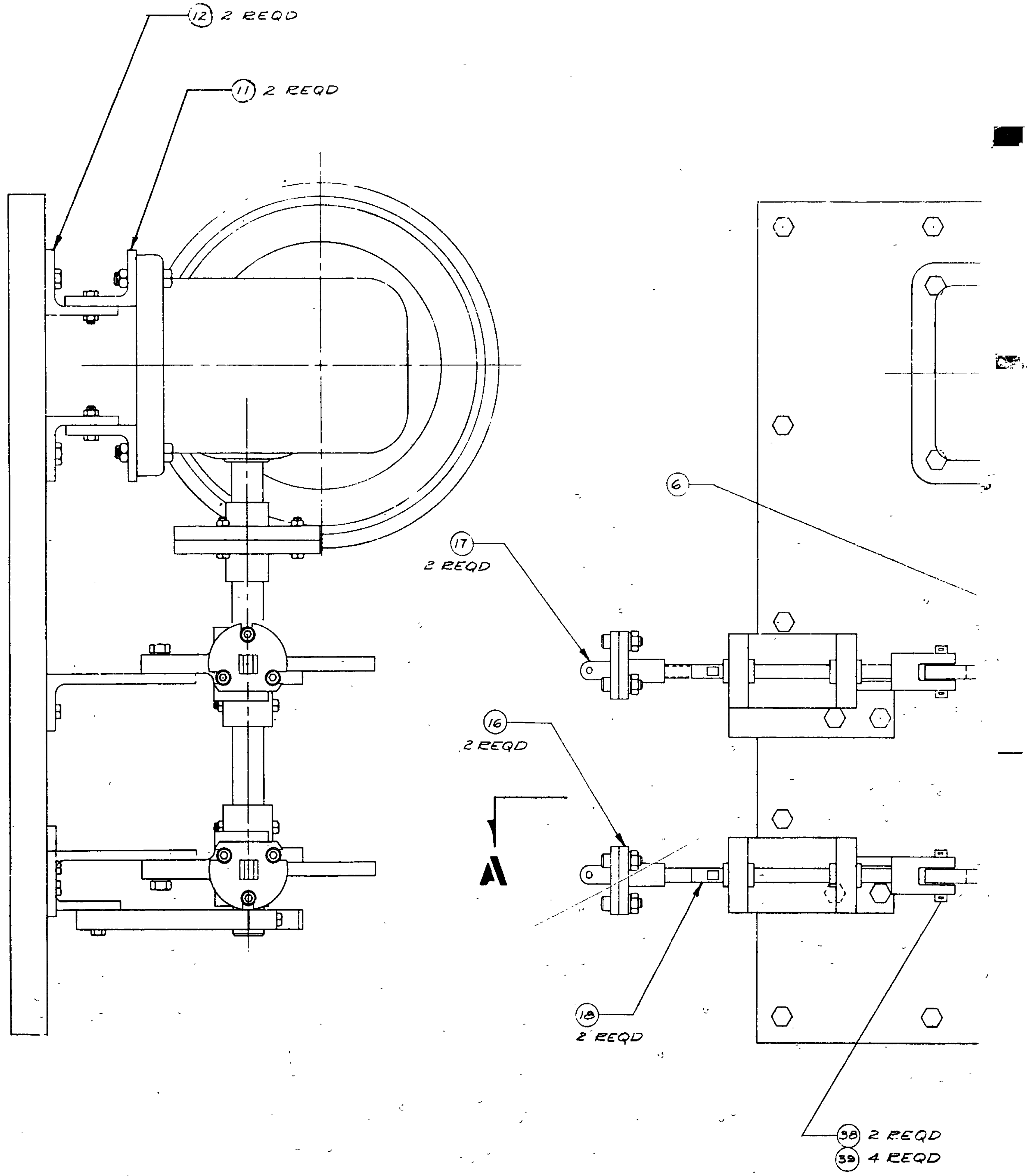
to operate in approximately a single axis mode. Specimen alignment is achieved by two ceramic pads supporting the rear end of the hub and by the third support point of the contacting specimens.

The specimen holders and test specimens were designed with the bulk of the cross-sections square in order to key the specimen to the hub during rotary motion.

Heaters were similar to those used in the static test apparatus. The heaters were alumina bodies with tantalum resistance elements.

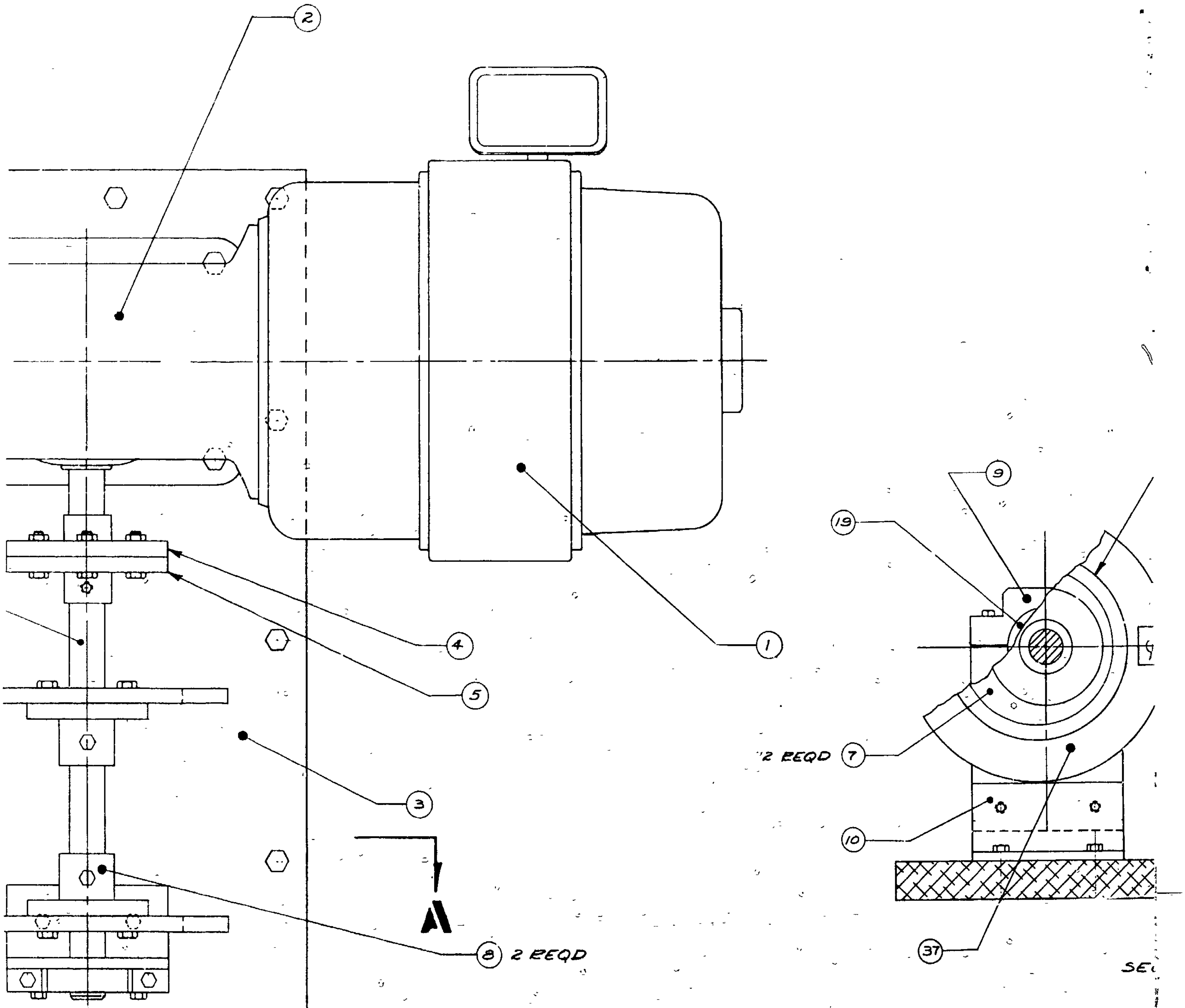
Figure 6 shows the drive mechanism assembly. A 1750-rpm motor of 1 HP (Boston 29494) powers the drive mechanism. A 10:1 flanged reductor (Boston UF 121E) provides 376 inch-pounds of torque at 175 rpm at its output shaft. The speed of the motor is controlled between 0 and 1750 rpm by a 1 HP "Ratiotrol" (Boston R-100). This shaft is coupled to a camshaft (item 6) which rotates two cams (item 7) against the inner races of two annular ball bearings (item 22).

Outer rings (item 37) attached to the ball bearing outer races are pinned to clevises (item 15) which are attached to the drive rods (item 18).



12 2 REQD
11 2 REQD
6
17
2 REQD
16
2 REQD
A
18
2 REQD
38 2 REQD
39 4 REQD

2



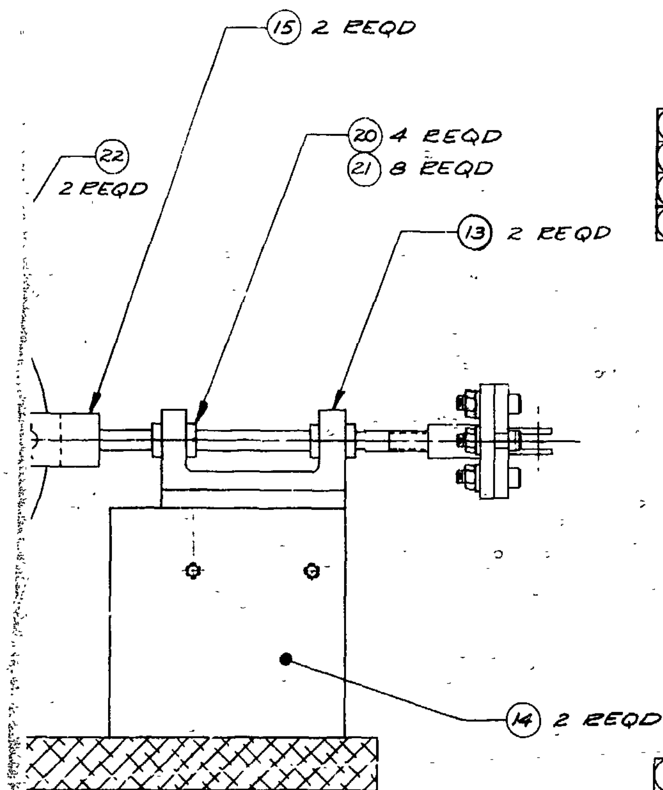
3 PROCURE FROM
MUSKEGON, MIC

2 PROCURE FROM
MANHASSET, N.Y

1 PROCURE FROM

NOTES: U.O.S

3



SECTION A-A

(1) KAYDON ENGINEERING CORP., ...CH.

(2) THOMSON INDUSTRIES CORP.,

(3) BOSTON GEAR WORKS, QUINCY, MASS.

	QTY REQD	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	ZONE	ITEM NO.
	4	MS24655-370	PIN COTTER		39
	2		PIN DOWEL -.312 O.D. X 1.38 LONG		38
	1	SP205941-31	OUTER RING		37
	1		1/4-20UNC-2B SET SCREW		36
	23		1/4-20UNC-2B HEX NUT		35
	26		3/8-16UNC-2B HEX NUT		34
	39		.25 I.D SPLIT LOCKWASHER		33
	18		.38 I.D. SPLIT LOCKWASHER		32
	49		.25 I.D. FLAT WASHER (STEEL)		31
	18		.38 I.D. FLAT WASHER (STEEL)		30
	8		1/4-20UNC-2A BOLT, .75 LONG (HEX HEAD)		29
	8		1/4-20UNC-2A BOLT, 1.00 LONG (HEX HEAD)		28
	5		1/4-20UNC-2A BOLT, 1.25 LONG (HEX HEAD)		27
	2		1/4-20UNC-2A BOLT, 1.75 LONG (HEX HEAD)		26
	6		1/4-20UNC-2A BOLT, 2.50 LONG (HEX HEAD)		25
	4		3/8-16UNC-2A BOLT, 2.00 LONG (HEX HEAD)		24
	14		3/8-16UNC-2A BOLT, 2.50 LONG (HEX HEAD)		23
3	2	KC40CP	BEARING, BALL, ANNULAR		22
2	8	W-375	EXTERNAL RETAINING RING		21
2	4	A-61014	BALL BUSHING		20
1	1	1640	BEARING, BALL, ANNULAR		19
	2	-78	DRIVE ROD		18
	2	-30	COUPLER ASSY FRONT		17
	2	-29	COUPLER ASSY REAR		16
	2	-32	CLEVIS		15
	1	-54	YOKE SUPPORT		14
	1	-55	YOKE		13
	2	-56	BRACKET MOUNT REDUCTOR--LOWER		12
	2	-57	BRACKET MOUNT REDUCTOR--UPPER		11
	1	-60	SUPPORT BASE		10
	1	-61	BEARING SUPPORT ASSY		9
	2	-62	CAM COLLAR		8
	2	-63	CAM		7
	1	-64	CAM SHAFT		6
	1	65	HUB--SHAFT FLANGE		5
	1	-66	HUB--REDUCTOR FLANGE		4
	1	SP205941-33	MOUNTING BASE PLATE		3
1	1	UF121E	FLANGED REDUCTOR		2
1	1	29494	MOTOR (1 HP)		1

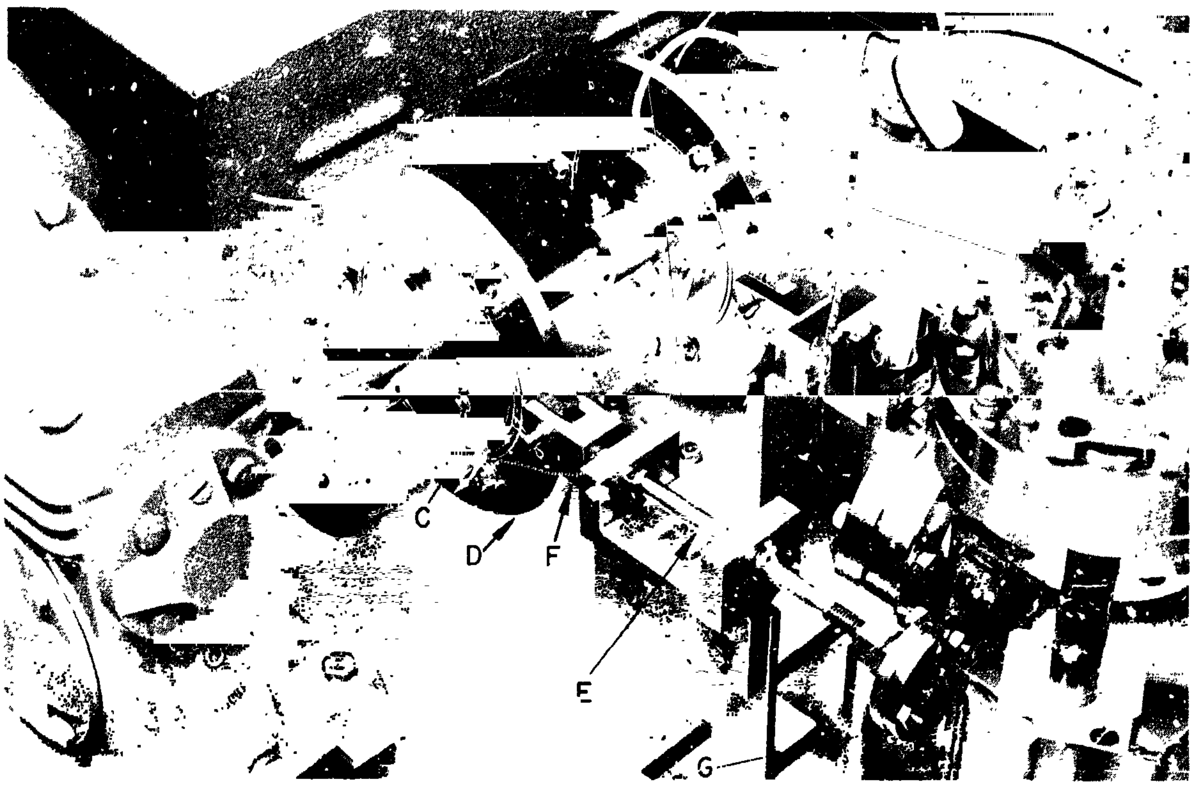
LIST OF MATERIALS

DRAWN S. FUJIKAWA	DATE 5 NOV '64	HUGHES	HUGHES AIRCRAFT COMPANY CULVER CITY, CALIF.
CHECKED J GARVEY	11-9-64	TITLE MOTOR DRIVE ASSY	
APPROVED		CODE IDENT NO. 82577	SIZE J — NUMBER SP205941-67
APPROVED		SCALE 1/2	SHEET

Figure 6. Motor drive assembly.

The drive rods are supported in ball bushings (item 20) attached to the base plate through yokes (item 13) and yoke supports (item 14). Coupler assemblies (items 16 and 17) connect the drive rods (item 18) to shafts which pass through the bellows to the vacuum chamber. The connection between the coupler assemblies and the shafts is made with dowel pins. The holes in the clevices through which the pins fit are elliptical to allow for lateral motion of the shafts during oscillation.

Figure 7 shows the drive mechanism. Figure 8 is an overall view of the equipment showing the drive mechanism, control panel, and instrumentation.



A. Reductor (Boston UF 121E)
B. Cam Shaft
C. Cam
D. Outer Ring
E. Drive Rod
F. Clevis
G. Flanged Connectors

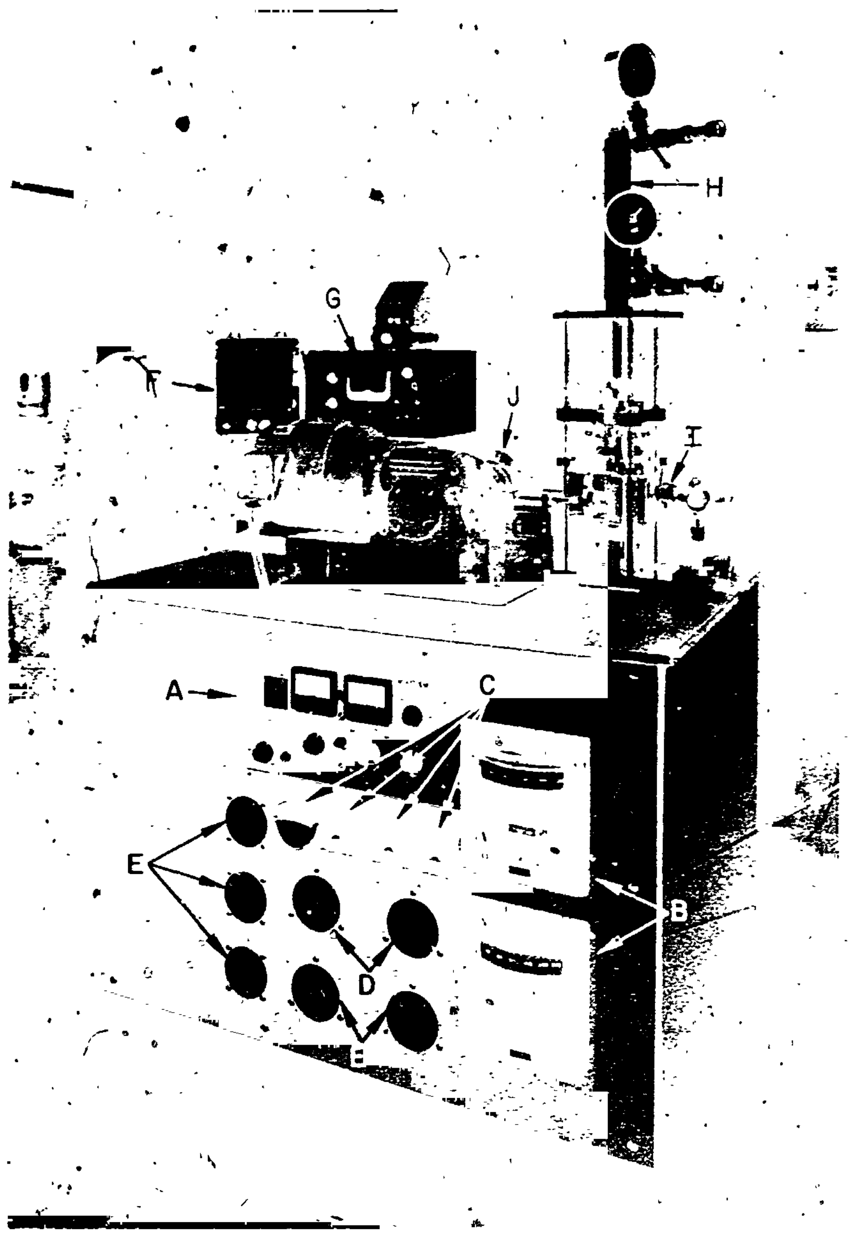
Figure 7. Drive mechanism. (Negative No. R103425)

G. Flanged Connectors

Figure 7. Drive mechanism. (Negative No. R103425)

2014 Aluminum/6 Al-4V Titanium

In a previous titanium/aluminum test at a nominal load of 3440 psi at 300C, no bonding occurred. Because aluminum bonded to a number of materials, a duplicate test of titanium/aluminum (couple No. 23) was made as shown in Table III. A strong bond was formed in 70,000 seconds in this test and a thin film of aluminum remained on the contact area of the titanium alloy specimen after the bond was broken. The apparent reason for bonding of the latter couple was that



A. Control Panel for Vac-ion Pump and Titanium Sublimation Pump

B. Controlling Pyrometers for Specimen Heaters

C. Voltmeters and Ammeters for Specimen Heaters

D. Variacs for Regulating Power to Specimen Heaters

E. Variacs for Regulating Power to Bake-out Tapes and Ion Pump Heaters

F. Varian G11A Recorder for Recording Strain Gage Voltage

G. Vactek Discharge Vacuum Gage Control

H. Double Acting Hydraulic Ram

I. Vacuum Chamber

J. Drive Mechanism

Figure 8: Assembled dynamic adhesion and cohesion test equipment. (Negative No. R103423)

VI. MATERIALS AND TEST SPECIMENS

Table I lists the test couples that were evaluated during the test program. All couples were tested under static conditions while only the first eleven couples were tested under dynamic conditions.

All materials were spectrographically analyzed for conformance with applicable specifications and the analyses are listed in Appendix B.

The configuration of the dynamic test specimens is shown in Figure 9. The area of the contacting surfaces of the upper specimen was varied from 0.025 square inch to 0.100 square inch, depending on the strength of the material, in order to limit the axial loads to the capacity of the strain link (5000 lbs).

Holes in the back sides of the specimens provided for thermocouple insertion.

The specimens were machined to drawing dimensions and the test surfaces were ground to a finish of CLA 19 to 37 microinches. All turning and grinding operations were performed with a chlorinated hydrocarbon cutting fluid in accordance with normal manufacturing procedures. Surface finishes were measured by a Taylor Hobson Surface Analyzer.

After their physical characteristics were measured, the specimens were vapor degreased in accordance with standard shop cleaning procedures set forth in MIL-S-5002 and then stored in clean dry boxes.

Before and after testing, Rockwell hardness measurements, dimensional measurements, and surface roughness measurements were made on all specimens. The specimens were photographed after testing and appropriate specimens were cross sectioned for microscopic examination of mating surfaces.

1. OFHC copper (annealed) versus OFHC copper (annealed)

2. AISI type 304 CRES (annealed) versus AISI type 304 CRES (annealed)

3. 2014 T-6 aluminum versus 2014 T-6 aluminum

4. 2014 T-6 aluminum versus AISI type 304 CRES (annealed)

5. René 41 (solution treated and aged) versus René 41 (solution treated and aged)

6. René 41 (solution treated and aged) versus 2014 T-6 aluminum

7. René 41 (solution treated and aged) versus AISI type 304 CRES (annealed)

8. A-286 steel (precipitation hardened) versus A-286 steel (precipitation hardened)

9. A-286 steel (precipitation hardened) versus 2014 T-6 aluminum

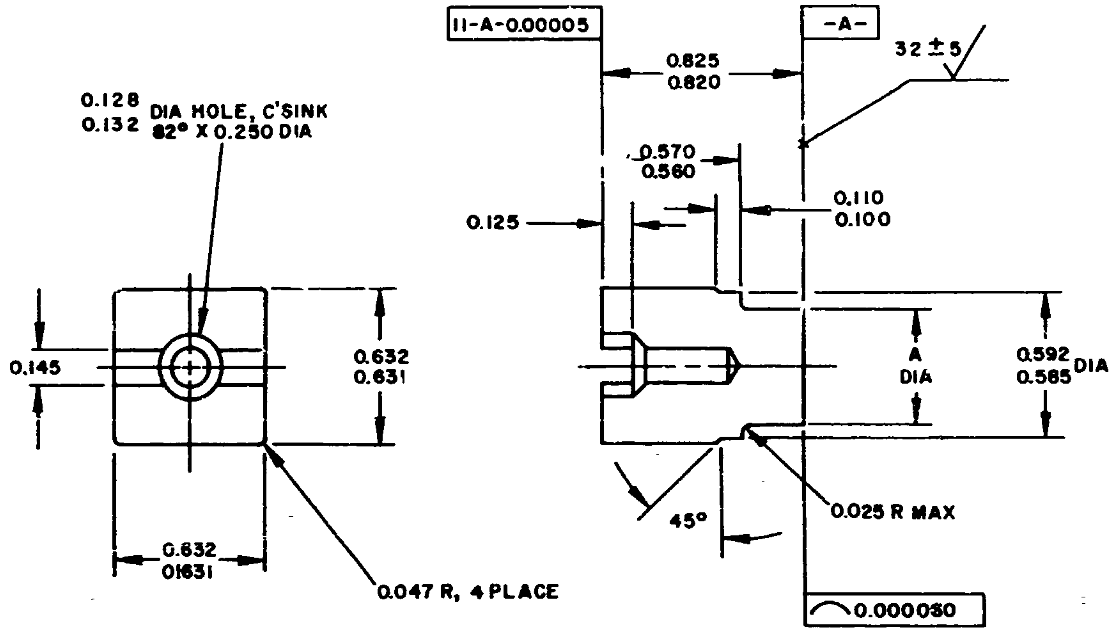
10. 6Al-4V-titanium alloy (precipitation hardened) versus 6Al-4V-titanium alloy (precipitation hardened)

11. 6Al-4V-titanium alloy (precipitation hardened) versus 2014 T-6 aluminum

12. A-286 steel (precipitation hardened) versus AISI type 304 CRES (annealed)

13. A-286 steel (precipitation hardened) versus René 41 (solution treated and aged)

Table I. Test couples.



DASH NUMBER	SPECIMEN	A ±0.005
80	LOWER	0.460
81	UPPER	

1. BREAK ALL SHARP EDGES

NOTE: UNLESS OTHERWISE SPECIFIED

Figure 9. Test specimens.

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VII. TEST PROCEDURES

STATIC TESTS

The static tests were made following the procedure described in Reference 1. The test specimens were installed in the vacuum chamber shown in Figure 2 and the system was baked out with the test specimens separated and maintained at the desired temperature. When the required vacuum of 5×10^{-9} torr was reached, the system was held at this vacuum for at least six hours with the specimens separated.

At each temperature, contacting loads were limited to 80 percent of the compressive yield strength of the weaker test material at temperature, or at a load at which no creep would occur, or 100,000 psi, whichever was lowest. Prescribed temperatures were 25, 150, 300 and 500C, except for couples containing the aluminum alloy. The maximum temperature for these couples was 300C.

The testing cycle was commenced by applying the desired contact load for 10 seconds and then determining the tensile force required to separate the specimens. Separation was performed at the same temperature used in applying the load. If no bonding occurred, the specimens were held in the separated position for 30 minutes and then the load was applied for 100 seconds. This procedure was repeated for successive time intervals of 1000, 10,000, and 70,000 seconds or until measurable adhesion or cohesion occurred. When this happened, the couple was removed from the test system for further analysis.

The test sequence was to conduct the initial tests under the conditions of maximum severity of contact pressure and temperature. The philosophy of this sequence was based on the assumption that a number of couples would not bond under these conditions and likewise would not bond at lower temperatures. When bonding occurred at the highest temperature, the tests were then repeated with new specimens at the next lower temperature in order to establish the temperature threshold of bonding.

DYNAMIC TESTS

Specimen conditioning in the vacuum chamber for the dynamic tests was the same as for the static tests. The test sequence is shown in Table II. In this Table, the high loads are the same as were used in static testing and the lower loads are fractions of the high loads as specified in the table.

In testing, the specimens were pressed together at a load of 12.5 percent of the high load. The upper specimen was oscillated ± 2 degrees at a rate of 3 cycles per second for the required time period while the lower specimen was held stationary. After oscillation, the specimens were separated. If no adherence occurred as indicated by the force required to separate the specimens, the test procedure was repeated at the next higher load and the forces of adherence measured. Until bonding was obtained, repetitive tests at increasingly severe loads, longer oscillatory periods, or higher temperatures were made in accordance with Table II. When bonding occurred, confirmatory tests were made and the specimens were removed from the vacuum chamber for further analysis.

Pressures measured by the Kreisman gauge were corrected to true pressure in accordance with the conversion chart of Figure 10 from Reference 2.

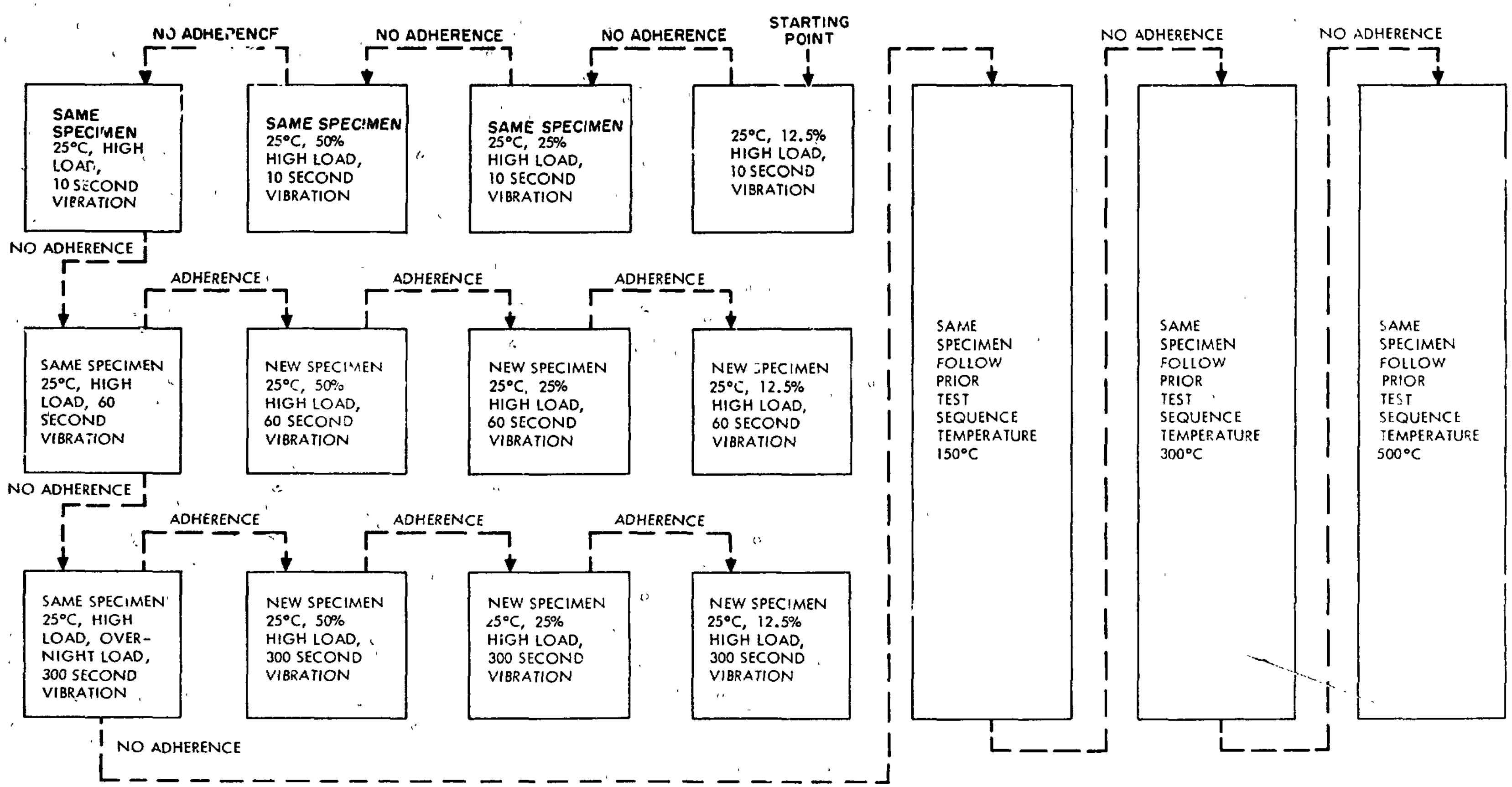


Table II. Flow diagram for test sequence.

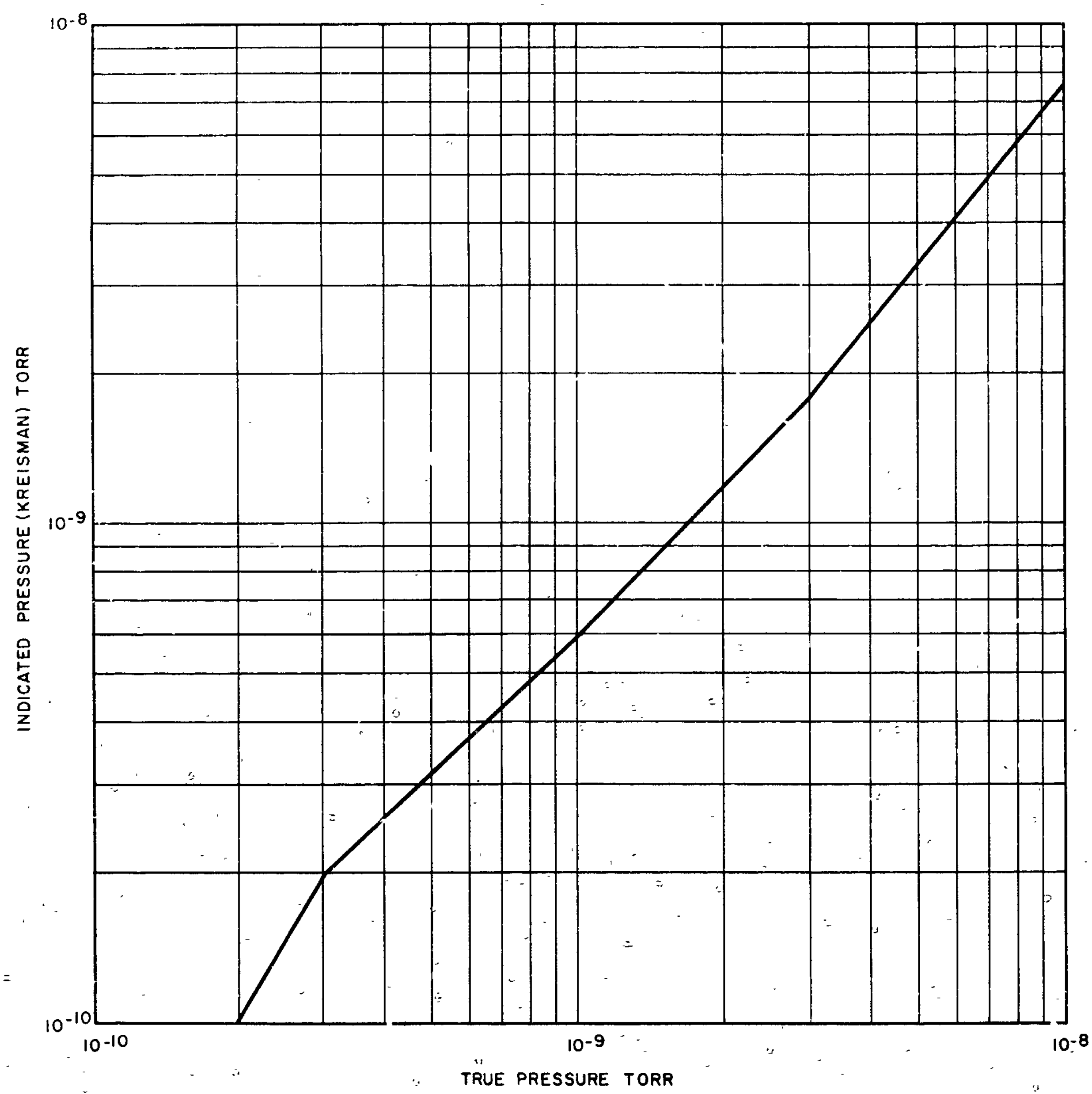


Figure 10. Pressure correction curve.

VIII. TEST RESULTS

STATIC TESTS

Static tests of the thirteen couples tested during the first year's program were reported in reference 1. In some of these tests the lower temperature threshold of adhesion and cohesion had not been determined. In other tests, the elastic limits of the materials were exceeded. The static tests reported below are additional tests of the same materials to more closely define the parameters of adhesion and cohesion.

Table III summarizes the test data including test times, temperatures, vacuum pressures, loads, and bond strengths. Table IV shows the physical measurements of the specimens before and after testing. This table indicates if the elastic limits of the specimens were exceeded and shows changes in the surface finishes.

Results of the individual tests are discussed below.

6Al-4V Titanium Couples

As reported in reference 1, the gas content of the titanium alloy prevented reaching pressures of 5×10^{-9} torr at elevated temperatures. Even with the addition of the titanium sublimation pump for the current tests this goal was not reached and except at 150C, the titanium couples were tested at higher pressures.

With couple No. 21 at 500C no cohesion occurred in periods up to 10,000 seconds, but in the 10,000 second test at a load of 58,000 psi, creep of the titanium took place. Therefore, for the 70,000 second test a lower load of 29,000 psi based on the creep strength of the alloy was selected. No cohesion occurred in this test.

Further testing of the 6Al-4V-titanium alloy (couple No. 34) resulted in no cohesion in the maximum time period at temperatures up to 300C. No cohesion occurred at 500C in time periods up to and including 10,000 seconds. The 70,000-second exposure was not completed due to accidental damage to the specimens.

304 Steel/A286 Steel Couple

Previous tests with this material combination had shown no adhesion under conditions of maximum severity. A286 steel had given difficulty in reaching the pressure of 5×10^{-9} torr. This test was repeated in an effort to reach this goal, but, it was not attained. The data agrees with the test of reference 1 in that no adhesion occurred at 500C.

A286 Steel/René 41 Couple

Previous tests with this material combination had indicated no adhesion under test conditions of maximum severity. The test was repeated for the same reason as for the 304 steel/A286 steel couple. Again, no adhesion took place, even under the severe load-time-temperature conditions shown in Table III.

17-4PH Steel Couple

Although this steel was not one of the specified test materials, it was tested because it was planned to use it in components of the dynamic test apparatus. To confirm that it has no adverse outgassing characteristics (as A286 steel does), it was tested at 500C. No cohesion occurred in 70,000 seconds.

Copper/Copper Couple

Previous tests showed that copper readily cohered to itself at 300C. This combination was tested again to determine its behavior at 150C and to gain additional information at 300C. No tendency toward cohesion was observed at 150C. Cohesion at 300C occurred at one-half the load of the previous test. The test specimens were made from cold rolled copper and the lower hardness after testing was due to annealing at the 300C test temperature.

2014 Aluminum/6 Al-4V Titanium

In a previous titanium/aluminum test at a nominal load of 3440 psi at 300C, no bonding occurred. Because aluminum bonded to a number of materials, a duplicate test of titanium/aluminum (couple No. 23) was made as shown in Table III. A strong bond was formed in 70,000 seconds in this test and a thin film of aluminum remained on the contact area of the titanium alloy specimen after the bond was broken. The apparent reason for bonding of the latter couple was that the contact area of the aluminum was smaller than in the former test. The load fluctuation (pounds) caused by thermal cycling of the heaters was similar in both tests, but the unit loading (psi) imposed by the thermal cycling was much greater in the specimen with the smaller area. Consequently the intended stress was exceeded and the aluminum specimen was deformed plastically as noted in Table IV.

Additional tests of this material combination (couple No. 32) resulted in no adhesion at 150C.

2014 Aluminum/A286 Steel

Additional tests of this material combination showed no tendency toward adhesion at 150C. Couple No. 24 did not adhere at 300C but couple No. 31 formed a weak bond in 10,000 seconds. However, there was slight plastic deformation of the aluminum alloy specimen in the latter test as noted in Table IV.

2014 Aluminum/René 41

Couple No. 25 formed a strong bond at 300C in 70,000 seconds. There was no adhesion of couple No. 30 at 150C, but adhesion occurred at 300C in 70,000 seconds, confirming the results of the first test. A third couple (No. 33) showed no adhesion at 150C and also none at 300C.

304 Steel/2014 Aluminum

In the test of couple No. 26 at 300C, adhesion was obtained in the 70,000 second period. No adhesion occurred with couple No. 35 at 150C in all time periods up to and including 70,000 seconds. At 300C, the couple adhered in 1000 seconds, but a malfunction of the strain gauge circuit caused overloading of the couple and the elastic limit of the aluminum alloy was exceeded as noted in Table IV.

2014 Aluminum/2014 Aluminum

Cohesion of couple No. 27 was demonstrated only in the 70,000 second period at 300C. Previous tests of aluminum alloy couples had shown no tendency toward cohesion a. 150C.

Changes in Surface Finishes of Test Specimens

The surface finish measurements of the test specimens shown in Table IV are not significant in terms of bonding characteristics. In general, the surfaces characteristics of the test specimens were not greatly changed by the static tests. Many of the measurements after testing do not represent the original surfaces because material had transferred from one specimen to the other in the process of bonding and breaking of the bond.

Cohesion in Air

Inasmuch as aluminum alloys form a protective oxide which does not decompose by volatilization in a vacuum, it would appear that this protective film would present a barrier to hinder bonding. Since the static tests in vacuum have indicated that bonding does occur at 300C, the evidence points to some other mechanism for disruption of the oxide film to allow metal to metal contact. Other probable mechanisms are diffusion of the oxide into the metal at the elevated temperatures or mechanical disruption by the yielding of the localized asperities on the surface to cause fracture of the brittle oxide. From these considerations, it is conceivable that bonding could be obtained in ambient atmospheres even though the bulk yield strength of the aluminum is not exceeded. To substantiate this theory, bonding tests of 2014 aluminum to itself were made in air. These tests were not made using the adhesion and cohesion test apparatus and therefore it was not convenient to use the same design of test specimens. In the tests made in air, lap-shear specimens having faying surfaces of 1 square inch were used. Three couples were simultaneously heated at 300C and 3500 psi for 19 hours. The shear strength of the bonds when cooled to room temperature varied from a value so low that it broke in handling to a maximum of 205 psi. These values cannot be correlated with the tensile strengths of the bonds tested at 300C in the vacuum apparatus, but the latter are probably much stronger. These tests substantiated that cohesion of the aluminum alloy can take place in air without exceeding the bulk yield strength of the alloy or that even without a vacuum static bonding can take place at 300C.

Couple No.	Couple	Test Time Seconds	Temperature, °C	Pressure, 10^{-9} torr	Load psi	Bond Strength psi	Remarks
21	Top Specimen Ti-6Al-4V No. Ti-7	10	500	25	58000	0	
		100	500	25	58000	0	
		1000	500	25	58000	0	Pressure increased to 4.4 x 10^{-8} torr at end of test.
	Lower Specimen Ti-6Al-4V No. Ti-9	10000	490-505	25	43000 58000	0	Pressure increased to 4.5 x 10-8 torr during test.
		70000	500	20	18500 29400	0	Load decreased to 43,000 psi due to creep of specimen.
34	Top Specimen Ti-6Al-4V No. Ti-8	10	150	3	83000	0	--
		100	150	3	83000	0	--
		1000	150	6	83000	0	--
	Lower Specimen Ti-6Al-4V No. Ti-11	10000	150	4	75000-84300	0	--
		70000	150	4	77800-83000	0	--
34	Top Specimen Ti-6Al-4V No. Ti-8	10	300	8	69000	0	--
		100	300	12	69000	0	--
		1000	300	32-50	68200-71600	0	--
	Lower Specimen Ti-6Al-4V No. Ti-11	10000	290-310	19-32	65400-69400	0	--
		70000	290-310	6-12	68200-70700	0	--

Table III. Test data.

Couple No.	Couple	Test Time Seconds	Temperature, °C	Pressure 10^{-9} torr	Load psi	Bond Strength psi	Remarks
34	Top Specimen Ti-6Al-4V No. Ti-8	10 100 1000	500 500 500	6×10^{-7} 4.6×10^{-7} 4.6 to 7×10^{-7}	29000 29000 29000	0 0	After the 10,000-sec test the upper specimen fell onto the lower specimen and damaged it resulting in increased surface contact area.
	Lower Specimen Ti-6Al-4V No. Ti-11	10000	500	5.5 to 10×10^{-7}	27700-30700	0	
22	Top Specimen 304 steel No. S_{35}	10 100	500 500	10 10	16000 16000	0 0	Pressure increased to 1.5×10^{-8} torr at end of test.
	Lower Specimen A286 steel No. S_26	1000	490-505	10	16000	0	Pressure increased to 2×10^{-8} torr at end of test.
		10000	490-505	10	15050 17500	0	Pressure increased to 1.5×10^{-8} torr at end of test.
		70000	490-505	10	15050 16500	0	Pressure decreased to 8×10^{-9} torr at end of test. Load decreased to 10300 psi for last 7 hours of test.

Table III (continued). Test data.

Couple No.	Couple	Test Time Seconds	Temperature, °C	Pressure 10^{-9} torr	Load psi	Bond Strength psi	Remarks
28	Top Specimen A286 steel No. S_2-9	70000	430-500	10	52200-72400	0	Pressure increased to 5 x 10^{-8} torr upon contact but decreased to 1 x 10^{-8} torr at the end of test.
	Lower Specimen Rene' 41 No. R-7						
29	Top Specimen 17-4 PH Steel No. S_7-1	10000	500	7	62300-67500	0	
	Lower Specimen 17-4 PH steel No. S_7-2	70000	500	6	64000-67500	0	
36	Top Specimen Copper No. C-2	10	150	4	5600	0	--
		100	150	4	5600	0	--
		1000	150	4	5300-5800	0	--
	Lower Specimen Copper No. C-2	10000	150	4	5100-5700	0	--
		70000	150	3.5-4	5500-5700		

Table III (continued). Test data.

Couple No.	Couple	Test Time Seconds	Temper-ature, °C	Pressure 10^{-9} torr	Load psi	Bond Strength psi	Remarks
36	Top						
	Specimen	10	300	3.5	1790	0	--
	Copper	100	300	3.5	1800	0	--
	No. C-2	1000	295-310	3.5	1790	0	--
	Lower						
	Specimen	10000	295-305	3.5	1790	0	--
	Copper						
	No. C-2	70000	300	3.5	1790	160	--
23	Top						
	Specimen	10	300	7	3440	0	
	2014 Al	100	300	7	3440	0	
	No. Al-4	1000	290-305	7	3440		
	Lower						
	Specimen	10000	295-310	7	3110-4500	0	Elastic limit of
	Ti-6Al-4V	70000	295-310	5	2560-5510	1785	2014 Al exceeded
	No. Ti-2						
32	Top						
	Specimen	10	150	5	25500	0	--
	2014 Al	100	150	6	25500	0	--
	No. Al-23	1000	150	7	24900-25900	0	--
	Lower						
	Specimen	10000	150	7	24900-26100	0	--
	Ti-6Al-4V						
	No. Ti-12	70000	150	7	24900-25900	0	--

Table III (continued). Test data.

Couple No.	Couple	Test Time Seconds	Temper-ature, °C	Pressure 10^{-9} torr	Load psi	Bond Strength psi	Remarks
24	Top Specimen 2014 Al No. Al-3	10 100 1000	300 300 300	4 3-4 4	3440 3440 3440	0 0 0	
	Lower Specimen A286 No. S_2-5	10000 70000	295-305 295-305	3-4 3-4	3440-4270 3440-3880	0 0	
31	Top Specimen 2014 Al No. Al-22	10 100 1000	150 150 150	4 4 6	25500 25500 25500	0 0 0	
	Lower Specimen A286 steel No. S_2-4	10000 70000	145-160 150	5-6 5	22800-25500 25500	0 0	
31	Top Specimen 2014 Al No. Al-22	10 100 1000	300 300 300	5 6 7	3440 3440 3440	0 0 0	
	Lower Specimen A286 steel No. S_2-4	10000	300	7	2700-3600	80	Creep strength was slightly exceeded.

Table III (continued). Test data.

Couple No	Couple	Test Time Seconds	Temperature, °C	Pressure 10^{-9} torr	Load psi	Bond Strength psi	Remarks
25	Top Specimen 2014 Al No. Al-9	10	300	5	2940	0	
		100	300	4-5	2940	0	
		1000	300	5	2940-3440	0	
	Lower Specimen Rene' 41 No. R-10	10000	300-315	4-5	1550-3440	0	
		70000	300	4	2330-3890	1750	
30	Top Specimen 2014 Al No. Al-21	10	150	3	25500	0	
		100	150	4	25500	0	
		1000	150	4	25580-27000	0	
	Lower Specimen Rene' 41 No. R-8	10000	150	4	25110-27000	0	
		70000	143-155	4	20500-26560	0	
30	Top Specimen 2014 Al No. Al-21	10	300	6	2940	0	
		100	300	5	3010	0	
	Lower Specimen Rene' 41 No. R-8	1000	300	5	2940-3220	0	
		10000	300	6	1880-3100	0	
		70000	300	4-5	2940	> 210	Recorder was set for too high sensitivity to measure total load.

Table III (continued). Test data.

Couple No.	Couple	Test Time Seconds	Temperature, °C	Pressure 10^{-9} torr	Load psi	Bond Strength psi	Remarks
33	Top Specimen 2014 Al No. Al-24	10	150	4	25500	0	--
		100	150	4	25500	0	--
		1000	150	5	24900-26100	0	--
	Lower Specimen Rene' 41 No. R-5	10000	150	6	23300-27000	0	--
		70000	150	5	25300-26600	0	--
33	Top Specimen 2014 Al No. Al-24	10	300	7	3440	0	--
		100	300	8	3440	0	--
		1000	300	8-31	3440	0	--
	Lower Specimen Rene' 41 No. R-5	10000	300	8-23	3150-3730	0	--
		70000	300	6-9	3070-3730	0	--
26	Top Specimen 304 steel No. S_3-6	10	300	5.5	2940	0	
		100	300	5.5	2940	0	
		1000	300	5.5	2940	0	
	Lower Specimen 2014 Al No. Al-19	10000	300	5.5	2940	0	
		70000	300	5.5	2200-2940	455	

Table III (continued). Test data.

Couple No.	Couple	Test Time Seconds	Temper-ature, °C	Pressure 10^{-9} torr	Load psi	Bond Strength psi	Remarks
35	Top Specimen 2014 Al No. Al-25	10	150	3.5	25500	0	--
		100	150	3.5	25500	0	--
		1000	150	3.5	24900-27000	0	--
	Lower Specimen 304 steel S3-11	10000	150	4	24000-26500	0	--
		70000	150	4-6	24700-26400	0	
35	Top Specimen 2014 Al No. Al-25	10	300	8	3400	0	--
		100	300	8	3400	0	--
		1000	300	7 5	--	165	Couple was loaded above elastic limit of aluminum alloy.
	Lower Specimen 304 steel No. S3-11						
27	Top Specimen 2014 Al No. Al-10	10	300	4	2940	0	
		100	300	4	3260	0	
		1000	300	4	3260	0	
	Lower Specimen 2014 Al No. Al-18	10000	290-300	4	1550-2940	0	
		70000	290-320	4	2490-3440	850	

Table III (continued). Test data.

Couple No.	Material	Specimen Number	Specimen Height, inches		Specimen Diameter inches		Specimen Hardness Rockwell		Surface Finish CLA, Microinches	
			Before	After	Before	After	Before	After	Before	After
21	Ti-6Al-4V	Ti-7	0.818	0.806	0.178	0.180	Rc37	Rc37	27	29
	Ti-6Al-4V	Ti-9	0.822	0.822	0.566	0.566	Rc37	Rc36	28	28
34	Ti-6Al-4V	Ti-8	0.824	0.725	0.177	0.257	Rc36	Rc36	27	*
	Ti-6Al-4V	Ti-11	0.823	0.823	0.565	0.565	Rc37	Rc37	19	*
22	304 steel	S_3-5	0.820	0.820	0.254	0.254	30T78	30T79	33	25
	A286 steel	S_2-6	0.822	0.822	0.566	0.566	Rc32	Rc32	31	24
28	A286 steel	S2-9	0.823	0.823	0.178	0.178	Rc33	Rc31	29	25
	Pene'41	R-7	0.823	0.823	0.566	0.565	Rc44	Rc44	33	28
27	17-4 PH steel	S_7-1	0.822	0.821	0.254	0.254	Rc37	Rc37	22	28
	17-4 PH steel	S_7-2	0.823	0.822	0.563	0.562	Rc34	Rc34	21	16
36	Copper	C-2	0.824	0.824	0.357	0.360	15T79	15T34	--	13
	Copper	C-22	0.821	0.821	0.567	0.567	15T80	15T37	24	19
23	2014 Al	Al-4	0.824	0.803	0.186	0.194	15T85	15T63	28	22
	Ti-6Al-4V	Ti-2	0.823	0.823	0.564	0.564	Rc36	Rc36	31	20
32	2014 Aluminum	Al-23	0.824	0.824	0.254	0.254	15T86	15T60	22	22
	Ti-6Al-4V	Ti-12	0.823	0.823	0.564	0.564	Rc37	Rc38	19	22

*Surface finish not measured due to damaged surfaces of specimens. Deformation of specimen Ti-8 was due to accidentally dropping top specimen onto lower specimen.

Table V. Physical measurements of test specimens.

Couple No.	Material	Specimen Number	Specimen Height, inches		Specimen Diameter, inches		Specimen Hardness Rockwell		Surface Finish CLA, Microinches	
			Before	After	Before	After	Before	After	Before	After
24	2014 Al	Al-3	0.824	0.824	0.186	0.186	15T83	15T62	31	16
	A286 steel	S_2-5	0.824	0.824	0.566	0.566	Rc31	Rc31	26	30
31	2014 Al	Al-22	0.823	0.820	0.254	0.257	15T85	15T62	22	18
	A286 steel	S_2-4	0.824	0.824	0.565	0.565	Rc33	Rc32	27	26
25	2014 Al	Al-9	0.824	0.824	0.186	0.187	15T83	15T61	27	23
	Rene' 41	R-10	0.824	0.824	0.566	0.566	Rc43	Rc43	27	28
30	2014 Al	Al-21	0.824	0.823	0.253	0.254	15T85	15T63	22	17
	Rene' 41	R-8	0.823	0.823	0.565	0.565	Rc43	Rc43	27	35
32	2014 Aluminum	Al-24	0.823	0.820	0.254	0.256	15T37	15T61	23	30
	Rene' 41	R-5	0.824	0.824	0.566	0.566	Rc43	Rc43	29	29
26	2014 Al	Al-19	0.822	0.822	0.564	0.565	15T86	15T58	31	28
	304 steel	S_3-6	0.819	0.819	0.254	0.254	30T79	30T76	27	28
35	2014 Aluminum	Al-25	0.824	0.798	0.254	0.275	15T87	15T62	21	17
	304 Steel	S_3-11	0.824	0.824	0.565	0.565	30T80	30T82	25	31
27	2014 Al	Al-10	0.820	0.820	0.186	0.186	15T87	15T59	22	27
	2014 Al	Al-18	0.825	0.825	0.565	0.565	15T87	15T54	24	28

Note: Diameter of specimen after test is maximum diameter of test portion of test specimen.

Table IV (continued). Physical measurements of test specimens.

DYNAMIC TESTS

Test data and physical measurements of the test specimens are tabulated in Figures 11 through 37. The physical measurements data provide a record of whether the elastic limits of the test materials have been exceeded and show differences in surface finishes before and after testing. The test results of the individual couples are also shown graphically in figures following the tabulation. The results are discussed in the following paragraphs.

A286 Steel to A286 Steel (Figures 11 and 12)

The threshold of bonding was 19,500 psi or 25 percent of the maximum allowable load when tested at room temperature for 10 seconds of oscillation. Additional tests made at higher loads and also a repeat test at the same load confirmed the bonding. The degree of bonding varied even with the same load, but this is probably a function of the changes in the contacting surfaces with repeated tests. The surface finish is changed by the rubbing of the specimens together. Also, the longer the specimens are held in the separated position between tests, the greater the opportunity to form surface films and inhibit cohesion in the subsequent test. The results show that the bond strength for a given load was inversely proportional to the time of separation between tests. Little change was noted in the surface roughness measurements after testing.

304 Steel to 304 Steel (Figures 13 and 14)

The threshold of bonding with this couple was 7000 psi or 25 percent of the maximum allowable load when tested at room temperature for 10 seconds of oscillation. A malfunction of the recorder prevented measurement of bond force in tests no. 2 and 3, but there were audible indications that bonding occurred in these tests. There was no significant change in the surface roughness of the specimens.

2014-T6 Aluminum to 2014-T6 Aluminum (Figures 15, 16, 17, and 18)

Tests made with two separate 2014 aluminum couples are presented. The data shown in Figures 15 and 16 are not considered valid because the upper specimen was partially annealed by excessive bake-out heat. This decreased the hardness of the specimen from Rockwell 15T-87 to 77 and plastic deformation occurred in loading as noted in Figure 15. It is noted that in this soft condition, no cohesion occurred at room temperatures under the most severe load of 46000 psi for 300 seconds of oscillation plus an overnight static load. However, at 150C a bond strength of nearly 80 percent of the applied load was obtained in 10 seconds of oscillation with a load of 3200 psi. The surface roughness of both specimens was increased considerably from the rupture of this strong bond.

The tests shown in Figures 17 and 18 were made with loads within the elastic limits of the alloy. These tests confirm the lack of bonding at room temperature. Bonding was obtained under the same test conditions as the previous couple (10 seconds of oscillation at 3200 psi and 150C). However, the bond strength was only 4 percent of that of the couple which was plastically deformed. The bond strength at a load of 6375 psi was less than at a load of 3200 psi, but increased with the load of 12750 psi. The surface finish of one specimen was rougher after the test, but the other was smoother.

Rene' 41 to Rene'41 (Figures 19, 20, and 21)

Two couples of Rene'41 were tested because the data on the first couple was invalidated by accidentally dropping the upper test specimen on to the lower specimen. This caused deformation of the upper specimen and a slight indentation in the lower specimen. When the specimens were contacted for testing, the mating surface areas did not coincide with the areas contacted when the upper specimen was dropped. This is evident in the specimen photographs of Figure 19. Consequently, the true area of contact was much less than the theoretical area and it is assumed localized yielding of the metal occurred. This would account for ease of bonding, i. e. at a low load of 13700 psi. Variations in bond strength with the same load are shown. This is undoubtedly due to vari tions in true contacting areas with successive tests. The surface roughnesses of both specimens were increased.

In the second series of tests (Figures 20 and 21) Rene' 41 bonded to itself at relatively low loads, but higher than the indicated loads of the damaged specimens of the first series. Bonding was demonstrated in repeated tests at 25000 psi or 25 percent of the maximum allowable load at room temperature for 10 seconds of oscillation. For some unknown reason no bonding was observed at higher loads. Bonding may have occurred in these tests but the bonds were ruptured in shear by elastic relaxation as the compressive load was removed and prior to application at the tensile force to measure the bond strength. Changes in surface roughnesses were minor.

Titanium-6Al-4V to Titanium-6Al-4V (Figures 22, 23, and 24)

Due to a change in the power supply for the strain gage circuit with a resultant decrease in current, the axial loads exceeded these intended for specimens 11A and 12A (Figures 22). However, as shown in Figure 22, the elastic limit of the alloy was not exceeded. The lowest load at which bonding was attained was 124000 psi at room temperature for 300 seconds of oscillation plus an overnight static load. There was hardly any change in the surface roughness of the specimens. Data from the tests of the second couple where the maximum loads were limited to 100000 psi at room temperature are shown in Figure 23. The pressure for this test was one order of magnitude higher than in the previous test. With this limiting load, no bonding took place at room temperature. Data from both couples is shown graphically in Figure 24.

It appears that the titanium alloy does not bond so r adily as the previously tested materials.

Copper to Copper (Figures 25 and 26)

Copper bonded to itself very reauily at a load of 930 psi applied for 10 seconds of oscillation at room temperature. A second test where the applied load was doubled gave over a four-fold increase in bond strength. The areas of cohesion are very evident in the photograph of Figure 25 and are concentrated mainly near the periphery of the contact area (where maximum relative movement of faying surfaces occurs). Based on the true area of cohesion which was about 30 percent of the contact area, the bond strength was about 1400 psi. The surface roughnesses were increased by the tests.

304 Steel to 2014 T6 Aluminum (Figures 27 and 28)

This couple showed no inclination to bond under loading conditions of maximum severity at room temperature. There were isolated instances of weak bonding at 150C, but the results were inconsistent. Bonds stronger that the applied loads of 1000 to 1500 psi were obtained at 300C in 10 seconds of oscillation. The non-uniform wear patterns of the specimens shown in the photograph of Figure 27 was caused by disassembly of the apparatus after the room temperature test. In re-assembly the new contact areas did not coincide with the original contact areas. The surface roughnesses of both specimens was increased. Softening of the aluminum alloy specimen was caused by the test temperature, but its elastic limit was not exceeded.

304 Steel to Rene' 41 (Figures 29 and 30)

This couple did not bond at room temperature under the test conditions of maximum severity. Weak bonds formed at 150C at loads of 6000 psi or 25 percent of the maximum allowable load when oscillated for 10 seconds. The surface roughnesses increased moderately.

2014-T6 Aluminum to A286 Steel (Figures 31 and 32)

The behavior of this couple was similar to that of previously tested dissimilar couples containing the aluminum alloy in that no adhesion occurred at room temperature. The specimens adhered at 150C at loads as low as 6400 psi or 25 percent of the maximum allowable load, but did not always adhere at higher loads. Changes in surface roughnesses of the specimens were not pronounced. Aside from changes in specimen surface characteristics with repeated tests that might affect the reproducibility, it is postulated that specimen geometry and differences in mechanical properties of the two materials may affect the measured adhesion. This theory is discussed below.

When dissimilar metal couples were tested, the weaker of the two materials was generally the specimen with a smaller contacting area to assure no overlapping of the specimens when they mated. When an axial load is applied to the couple, two factors are operating together to cause greater lateral elastic deformation of the weaker material than of the stronger material. First, the lateral deformation is inversely proportional to the modulus of elasticity and secondly, inversely proportional to the cross sectional area. This means that when a compressive load is applied to the couple, the contacting area of the smaller diameter specimen will expand a greater amount laterally than will the contacting area of the larger specimen. Likewise when the compressive load is released, the smaller specimen will contract laterally and if it is adhered to the mating specimen, the bond will be subjected to shear forces. These forces will be maximum at the periphery of the specimen. If the bond is weak, it is conceivable that it would break in shear so that no measurable adhesion is recorded when the specimens are unloaded by applying a tensile force.

Sample calculations as related to the test of 2014 aluminum to A286 steel is support of this theory are given. The data for this test are shown in Figure 34. The first measurable adhesion was found when loaded at 6400 psi at 150C, but no adhesion was found at a load of 12800 psi.

The following terms and equations are used:

δ_a = axial strain

δ_l = lateral strain

S_a = axial stress

S_s = shear stress

E_c = modulus of elasticity in compression

G = shear modulus

δ_s = shear strain

μ = Poissons ratio

(1) $\delta_a = \frac{S_a}{E_c}$

(2) $\delta_1 = \mu \, \delta_a$

(3) $\delta_s = \frac{S_s}{G}$

The cross sectional area of the 2014 Al specimen = 0. 100 square inches and of the A286 specimen = 0. 167 square inches. At a temperature of 150C the mechanical properties of 2014 aluminum are reduced to 0. 86 of room temperature properties and the properties of A286 are reduced to 0. 94.

Strains for the 2014 aluminum specimen: At a load of 6400 psi at 150C

$$\delta_a = \frac{6.4 \times 10^3}{.86 \times 10.7 \times 10^6} = 6.95 \times 10^{-4} \text{ in/in.}$$

$$\delta_1 = .33 \times 6.95 \times 10^{-4} = 2.45 \times 10^{-4} \text{ in/in.}$$

Strains for the A286 steel specimen: At a load of 6400 psi on a cross sectional area of 0. 100 square inchs which is being transmitted to the steel specimen having a cross sectional area of 0. 167 square inches it is assumed that the stress on the smaller area is transmitted to the entire cross section of the larger member.

$$\delta_a = \frac{6.4 \times 10^3}{.94 \times 29.1 \times 10^6} \times \frac{.100}{.167} = 1.4 \times 10^{-4} \text{ in/in.}$$

$$\delta_1 = .33 \times 1.4 \times 10^{-4} = 0.46 \times 10^{-4} \text{ in/in.}$$

Lateral movement at the faying surfaces: From application or release of the compressive load, the lateral movement of the aluminum alloy specimen relative to the steel specimens will equal the difference in δ_1 of the two specimens which is:

$$2.45 \times 10^{-4} - 0.46 \times 10^{-4} = 1.99 \times 10^{-4} \text{ in/in.}$$

Shear Stress: If the specimens adhere under the compressive load, when the load is removed

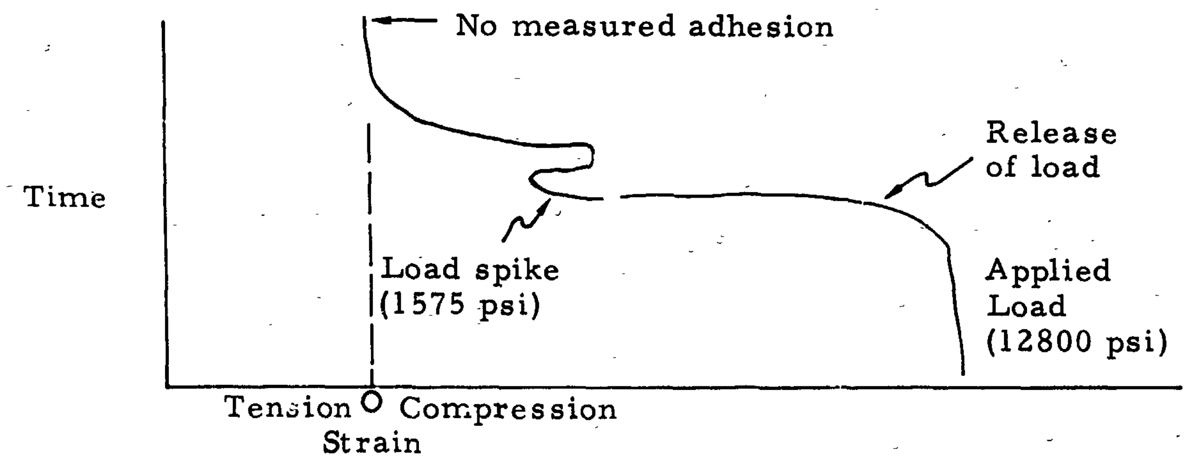
$$\delta_s = \delta_1 \text{ or } 1.99 \times 10^{-4} \text{ in/in.}$$

The maximum shear stress in the aluminum alloy when loaded to 6400 psi

$$S_s = S_s G(0.86) = 1.99 \times 10^{-4} \times 4 \times 10^{6} \times 0.86 = 685 \text{ psi}$$

Now if the compressive load is doubled (12800 psi), the shear stress of the adhered specimens is likewise doubled to 1370 psi when the compressive load is released.

Behavior of 2014 aluminum/A286 couple at a load of 12800 psi. The chart recording the strain in this test had the following appearance:



As the load was being released, a load spike occurred at 1575 psi compression and the load instantaneously increased to 2050 psi. This spike was accompanied by a sound normally observed in breaking the adhesive bond. The explanation for the momentary increase in load at this point is if the specimens are adhering, they are restrained from contracting as the load is reduced. When the bond is ruptured, there is a sudden lateral contraction which must be accompanied by an axial expansion. With the hydraulic loading system this would cause an increase in the load or pressure on the specimens.

If the specimens were completely adhered the amount of shear stress that would be developed in the above example when the load is reduced from 12800 psi to 1575 psi would equal 1250 psi. This compares with the calculated shear stress of 685 psi when the specimens are loaded to 6400 psi.

These calculations indicate only the maximum shear stress developed at the periphery of the contact area. At the center of the bonded area the relaxation with release of the load (and shear stress) would approach zero. Thus the magnitude of the shear stress is dependent upon the mode of bonding. If the specimens are bonded near the periphery the shear stress would be greater than if they were bonded at their center. The former mode of bonding was more prevalent in these tests. Figure 25 of a couple whose surfaces were not obscured by repeated tests shows that most of the bonding took place at the periphery. This is to be expected in an oscillatory test because maximum rubbing action occurs at the periphery.

In the case of weak bonds, it is believed that the shear stresses acting on the bond upon release of the axial load sometimes disrupt the bond. This is proposed as an explanation for anomalies found in the tests where adhesion is found at a one load, but not necessarily at higher loads.

2014-T6 Aluminum to Rene' 41 (Figures 33, 34 and 35)

There was no bonding of this couple (Figure 33) in all room temperature tests through the test conditions of maximum severity. The bonding was more consistent at 150C at loads of 3190 psi and 6380 psi than it was at loads of 12750 psi. In fact one test at the latter load gave no bonding. In two of the tests, multiple adhesion forces were recorded. The surface roughnesses of the specimens were increased slightly.

The data shown in Figure 34 is from a second test of 2014 aluminum/Rene' 41 in which the specimen with the smaller contacting surface was Rene' 41. The purpose of changing specimen geometry was to reduce the shear forces upon release of the compressive load as discussed under the 2014 aluminum/A286 steel couple. This would reduce the shear forces by approximately 78 percent compared to when the smaller specimen is the weaker of the two alloys. In this test, the behavior of the couple at room temperatures was similar to that of the first couple in that no adhesion occurred. At 150C adhesion did not occur at the lower loads as with the previous couple, but did occur at certain of the higher loads where no adhesion took place with the previous couple. While this test was not wholly conclusive in proving the shear theory, it did demonstrate adhesion with high loads.

Graphic data from both test couples are shown in Figure 35.

2014-T6 Aluminum to 6A1-4V Titanium (Figures 36 and 37)

No adhesion of this couple occurred in any of the room temperature tests. At 150C, adhesion took place at loads as low as 3200 psi or 12.5 percent of the maximum allowable. In some tests at higher loads, adhesion did not always occur. The surface roughness of the softer material (2014 aluminum) was increased while that of the titanium alloy was decreased slightly.

TEST RESULTS

FIG. 11
MAGNIFICATION 2.5 x
TOP A 286 Steel No. 9 A
BOTTOM A 286 Steel No. 10 B
NEGATIVE NO. 01863P

TOP BOTTOM

Test No.	Axial Load PSI	Temp. °C	Pressure, 10^{-10} Torr Measured Kreisman	Corrected	Time of Vibration Seconds	Bond Strength PSI	Time of Specimen Separation Between Tests
1	9750	22	2.0	3.0	10	0	
2	9750	22	3.0	4.7	10	0	55 minutes
3	9750	22	2.8	4.4	10	0	2 hours 35 minutes
4	19500	22	2.0	3.0	10	330	96 hours
5	39000	22	3.0	4.7	10	750	30 minutes
6	39000	22	2.8	4.4	10	560	19 hours
7	19500	22	2.5	3.9	10	430	30 minutes

TEST DATA

Material	Specimen Number	Specimen Height, In. Before	After	Specimen Diameter, In. Before	After	Hardness Rockwell Before	After	Surface Finish, CLA Before	After
A 286 steel	9A	0.973	0.973	0.181	0.181	R_c-33	R_c-35	35	38
A 286 steel	10B	0.973	0.973	0.461	0.461	R_c-36	R_c-34	37	42

PHYSICAL MEASUREMENTS OF TEST SPECIMENS

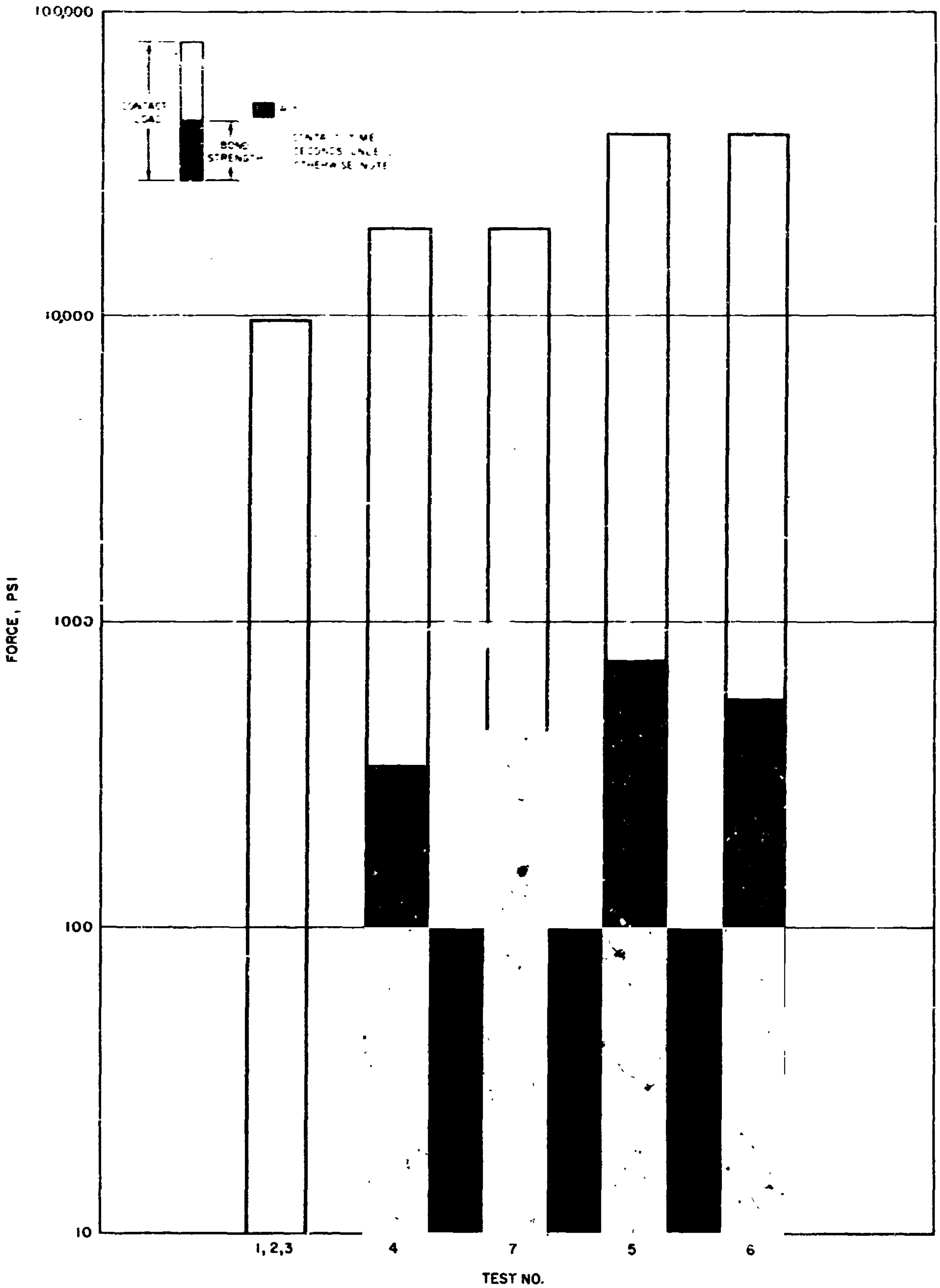


Figure 12. Contact loads versus bond strengths A286 steel/A286 steel.

TEST RESULTS

FIG. 13
MAGNIFICATION 2.5 x
TOP 304 Steel No. 3E
BOTTOM 304 Steel No. 4D
NEGATIVE NO. 01857P

TOP **BOTTOM**

Test No.	Axial Load PSI	Temp. °C	Pressure, 10^{-10} Torr Measured Kreisman	Corrected	Time of Vibration Seconds	Bond Strength PSI	Time of Specimen Separation Between Tests
1	3500	22	3.0	4.7	10	0	
2	7000	22	3.5	5.6	10	*	35 minutes
3	7000	22	3.2	5.0	10	*	10 minutes
4	7000	22	2.7	4.2	10	360	65 minutes

TEST DATA

* No measurement obtained

Material	Specimen Number	Specimen Height, In. Before	After	Specimen Diameter, In. Before	After	Hardness Rockwell Before	After	Surface Finish, CLA Before	After
304 steel	3E	0.973	0.973	0.255	0.255	30T-78	30T-79	34	35
304 steel	4D	0.975	0.975	0.460	0.460	30T-79	30T-81	28	28

PHYSICAL MEASUREMENTS OF TEST SPECIMENS

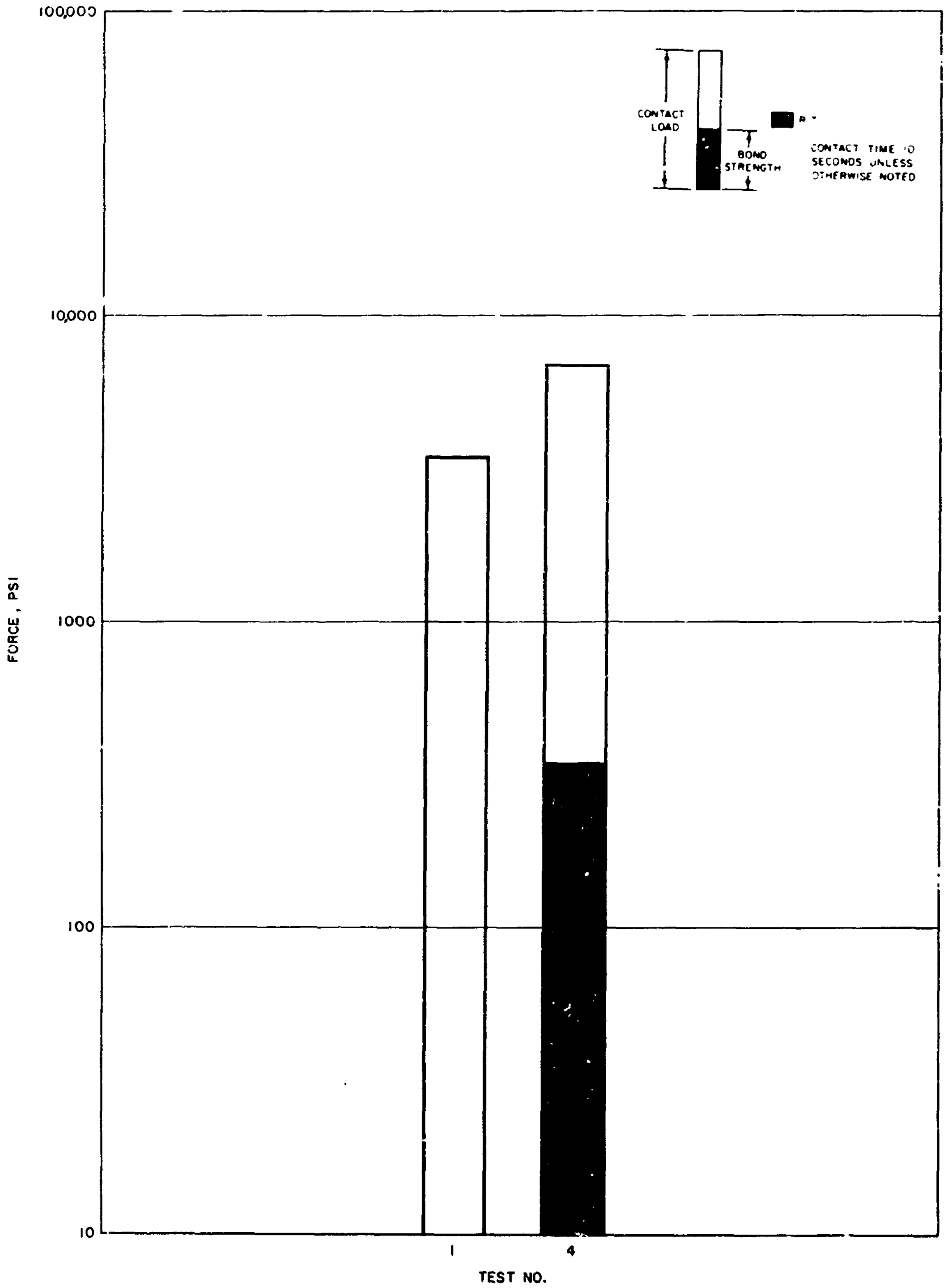


Figure 14. Contact loads versus bond strengths 304 steel/304 steel.

TEST RESULTS

FIG. 15
MAGNIFICATION 2. 5 x
TOP 2014-T6 Aluminum No. 5A
BOTTOM 2014-T6 Aluminum No. 6A
NEGATIVE NO. 01860P

TOP BOTTOM

Test No.	Axial Load PSI	Temp. °C	Pressure, 10^{-10} Torr Measured Kreisman	Pressure, 10^{-10} Torr Corrected	Time of Vibration Seconds.	Bond Strength PSI	Time of Specimen Separation Between Tests
1	5750	22	1. 5	2. 5	10		
2	5750	22	1. 0	2. 0	10	0	20 minutes
3	11500	21	2. 2	3. 4	10	0	2 hours 45 minutes
4	11500	22	2. 6	4. 0	10	0	20 minutes
5	23000	21. 5	1. 8	2. 9	10	0	25 minutes
6	46000	21	2. 4	3. 7	10	0	35 minutes
7	46000	21. 5	3. 0	4. 7	60	0	25 minutes
8	46000	21. 5	1. 8	2. 9	300(1)	0	30 minutes
9	3200	150	10. 0	17. 0	10	> 445(2)	2 hours 50 minutes
10	3200	150	10. 0	17. 0	10	>1290(2)	25 minutes
11	3200	150	6. 2	11. 0	10	2420	1 hour 40 minutes

TEST DATA

(1) In addition to 300 seconds of vibration, the static load of 46000 psi was applied for 16 hours.
(2) The recorder for strain measurement was set for high sensitivity and went off scale before the bond broke.

Material	Specimen Number	Specimen Height, In. Before	Specimen Height, In. After	Specimen Diameter, In. Before	Specimen Diameter, In. After	Hardness Rockwell Before	Hardness Rockwell After	Surface Finish, CIA Before	Surface Finish, CIA After
2014-T6	5A	0. 971	0. 961	0. 360	0. 368	15T-87	15T-77 (3)	20	90
2014-T6	6A	0. 975	0. 975	0. 461	0. 461	15T-87	15T-87	19	90

PHYSICAL MEASUREMENTS OF TEST SPECIMENS

(3) Excessive bakeout temperatures softened specimen

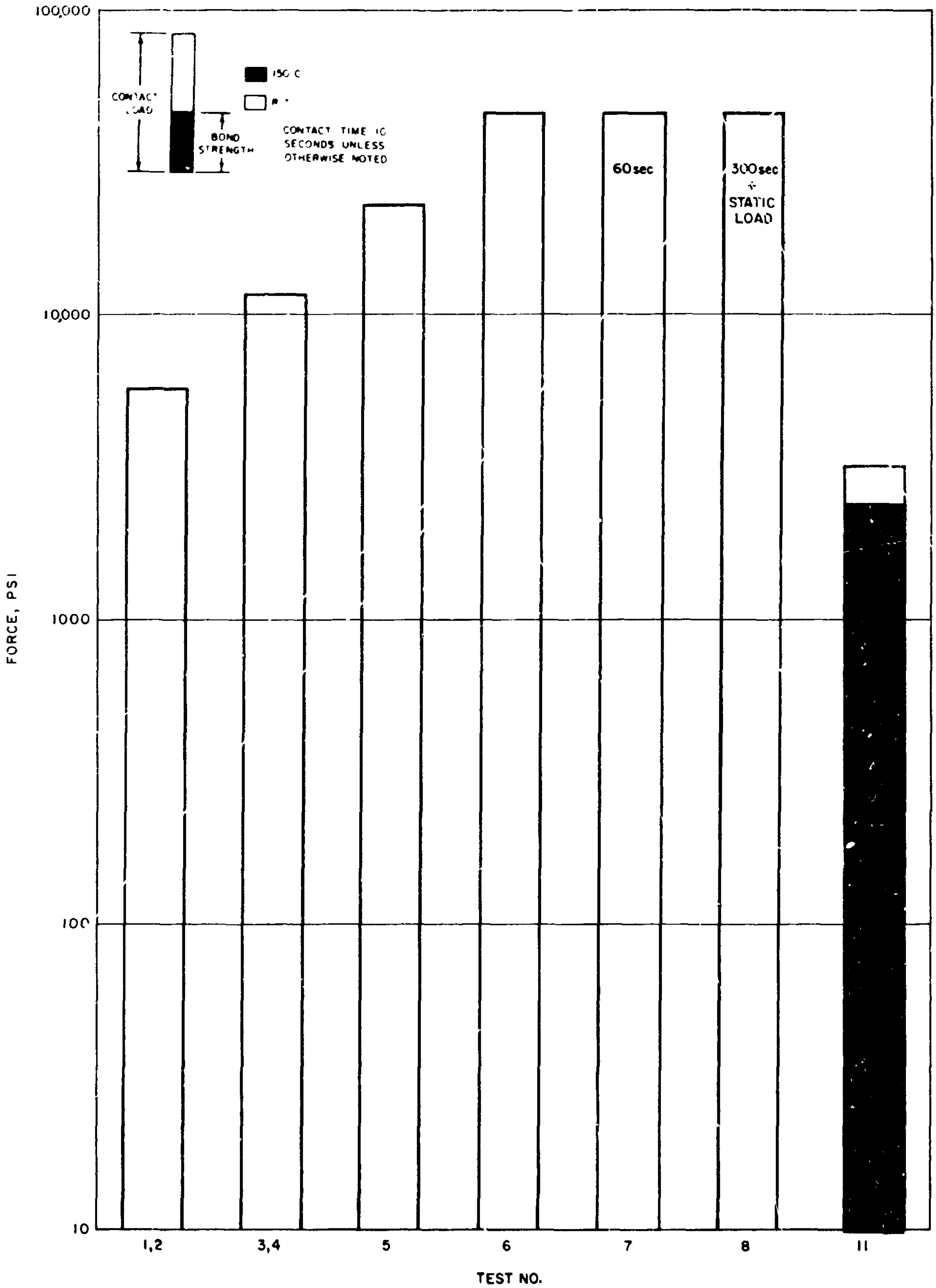
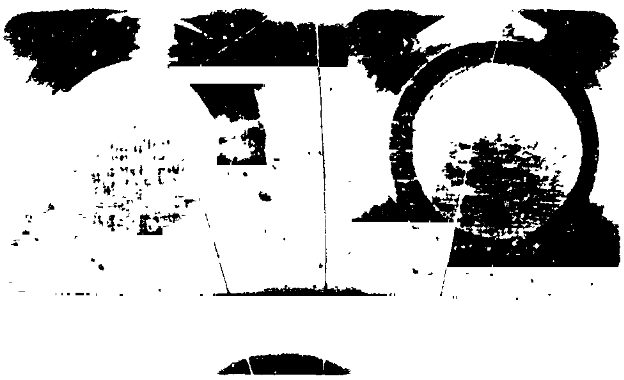


Figure 16. Contact loads versus bond strengths 2014-T6 aluminum/2014-T6 aluminum.

TEST RESULTS



TOP BOTTOM

FIG. 17
MAGNIFICATION 2.5 x
TOP 2014-T6 Aluminum No. 5F
BOTTOM 2014-T6 Aluminum No. 6C
NEGATIVE NO. 01935P

Test No.	Axial Load PSI	Temp. °C	Pressure, 10^{-10} Torr Measured Kreisman	Corrected	Time of Vibration Seconds	Bond Strength PSI	Time of Specimen Separation Between Tests
1	5750	22.5	1.0	2.0	10		
2	11500	22.5	1.5	2.5	10	0	10 minutes
3	23000	22.0	1.4	2.4	10	0	15 minutes
4	46000	22.5	2.3	3.5	10	0	10 minutes
5	46000	22.5	1.5	2.5	60	0	15 minutes
6	46000	22.5	1.8	2.7	300	0	10 minutes
7	3200	150	25.0	40.0	10	100	21 hours 35 minutes
8	3200	150	23.0	37.0	10	90	45 minutes
9	6375	150	42.0	62.0	10	50	45 minutes
10	12750	150	42.0	62.0	10	360	10 minutes

TEST DATA

Material	Specimen Number	Specimen Height, In. Before	After	Specimen Diameter, In. Before	After	Hardness Rockwell Before	After	Surface Finish, CIA Before	After
2014-T6	5F	0.975	0.975	0.361	0.361	15T-87	15T-86	18	12
2014-T6	6C	0.975	0.975	0.461	0.461	15T-86	15T-86	20	33

PHYSICAL MEASUREMENTS OF TEST SPECIMENS

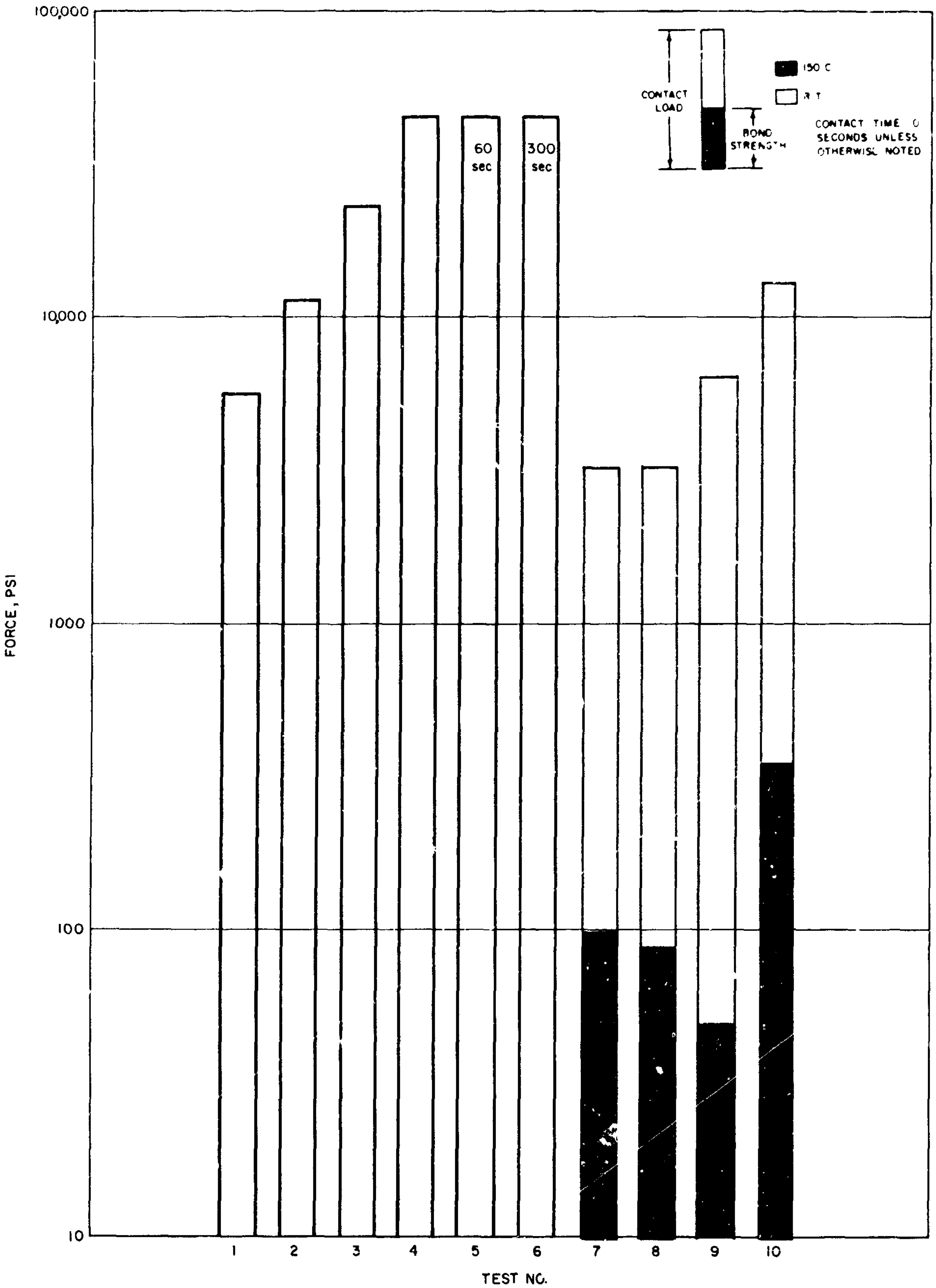


Figure 18. Contact loads versus bond strengths 2014-T6 aluminum/2014-T6 aluminum.

TEST RESULTS

FIG. 19
MAGNIFICATION 2.5 X
TOP Rene' 41 No. 7A
BOTTOM Rene' 41 No. 8A
NEGATIVE NO. 01862P

TOP BOTTOM

Test No.	Axial Load PSI	Temp. °C	Pressure, 10^{-10} Torr Measured Kreisman	Pressure, 10^{-10} Torr Corrected	Time of Vibration Seconds	Bond Strength PSI	Time of Specimen Separation Between Tests
1	13700	21	1.1	2.1	10	500	
2	13700	21	1.6	2.6	10	>2800(1)	25 minutes
3	13700	21	2.0	3.0	10	1300	30 minutes
4	13700	21	1.6	2.6	10	3200	15 minutes

TEST DATA

(1) The recorder for strain measurement was set for high sensitivity and went off scale before the bond broke.

Material	Specimen Number	Specimen Height, In. Before	Specimen Height, In. After	Specimen Diameter, In. Before	Specimen Diameter, In. After	Hardness Rockwell Before	Hardness Rockwell After	Surface Finish, CLA Before	Surface Finish, CLA After
Rene' 41	7A	0.975	0.958	0.181	0.187	R_c-42	R_c-42	25	40
Rene' 41	8A	0.975	0.975	0.460	0.460	R_c-41	R_c-42	20	31

PHYSICAL MEASUREMENTS OF TEST SPECIMENS

The top specimen was accidentally dropped on to the lower specimen before the test. This deformed the specimen and resulted in non-uniform contact during the tests.

TEST RESULTS

FIG. 20
MAGNIFICATION 2.5 x
TOP Rene' 41 No. 7B
BOTTOM Rene' 41 No. 8D
NEGATIVE NO. 01936P

TOP BOTTOM

Test No.	Axial Load PSI	Temp. °C	Pressure, 10^{-10} Torr Measured Kreisman	Corrected	Time of Vibration Seconds	Bond Strength PSI	Time of Specimen Separation Between Tests
1A	12500	22	1.0	2.0	10	70	
2A	25000	22	1.5	2.5	10	>920(1)	15 minutes
3A	25000	22	1.2	2.2	10	2880	10 minutes
4A	50000	22	1.5	2.5	10	0	10 minutes
5A	100000	22	1.1	21	10	0	10 minutes
6A	12500	23	1.5	2.5	10	870	10 minutes

TEST DATA

(1) The recorder for strain measurement was set for high sensitivity and went off scale before the bond broke.

Material	Specimen Number	Specimen Height, In. Before	After	Specimen Diameter, In. Before	After	Hardness Rockwell Before	After	Surface Finish, CIA Before	After
Rene' 41	7B	0.975	0.975	0.182	0.182	R_c-42	R_c-43	21	22
Rene' 41	8D	0.975	0.975	0.460	0.460	R_c-44	R_c-43	30	31

PHYSICAL MEASUREMENTS OF TEST SPECIMENS

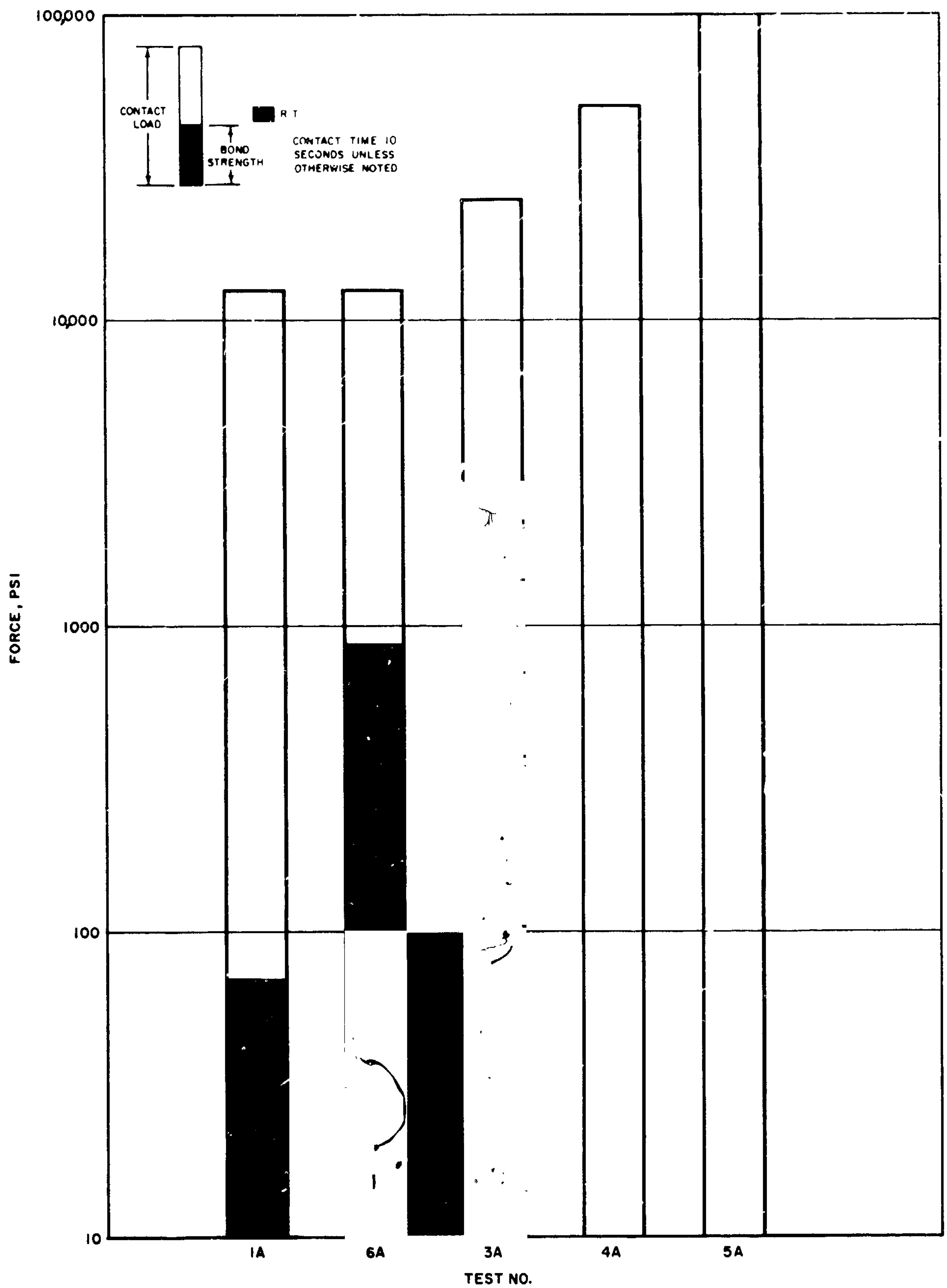
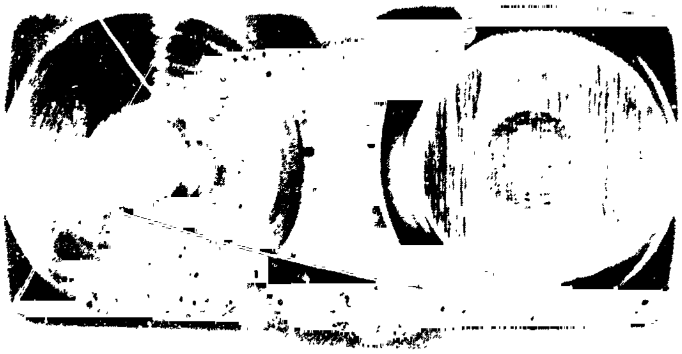


Figure 21. Contact loads versus bond strengths René 41/René 41.



TEST RESULTS

FIG. 22
MAGNIFICATION 2.5 x
TOP Ti-6Al-4V No. 11A
BOTTOM Ti-6Al-4V No. 12A
NEGATIVE NO. 01864P

TOP BOTTOM

Test No.	Axial Load PSI	Temp. °C	Pressure, 10^{-10} Torr Measured Kreisman	Pressure, 10^{-10} Torr Corrected	Time of Vibration Seconds	Bond Strength PSI	Time of Specimen Separation Between Tests
1	15500	21	3.0	4.7	10	0	
2	31000	21	2.6	4.0	10	0	20 minutes
3	62000	21	3.0	4.7	10	0	15 minutes
4	124000	21	3.6	5.8	10	0	15 minutes
5	124000	21	3.6	5.8	60	0	[illegible] minutes
6	124000	21	2.2	3.[illegible]	300(1)	750	[illegible] minutes

TEST DATA

(1) In addition to 300 seconds of vibration, the static load of 124000 psi was applied for 19 hours.

Material	Specimen Number	Specimen Height, In. Before	Specimen Height, In. After	Specimen Diameter, In. Before	Specimen Diameter, In. After	Hardness Rockwell Before	Hardness Rockwell After	Surface Finish, CLA Before	Surface Finish, CLA After
Ti-6Al-4V	11A	0.975	0.974	0.181	0.181	R_c-38	R_c-38	22	22
Ti-6Al-4V	12A	0.974	0.974	0.460	0.460	R_c-38	R_c-38	20	18

PHYSICAL MEASUREMENTS OF TEST SPECIMENS

TEST RESULTS

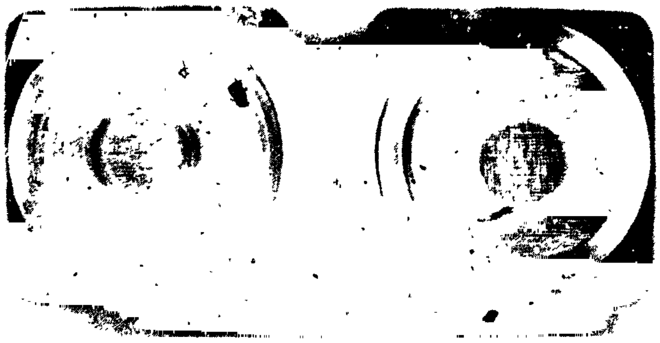


FIG.	23
MAGNIFICATION	2.5 x
TOP	Ti-6Al-4V No. 11B
BOTTOM	Ti-6Al-4V No. 12E
NEGATIVE NO.	01937P

TOP BOTTOM

Test No.	Axial Load PSI	Temp. °C	Pressure, 10^{-10} Torr Measured Kreisman	Pressure, 10^{-10} Torr Corrected	Time of Vibration Seconds	Bond Strength PSI	Time of Specimen Separation Between Tests
1A	12500	23	27.0	42.0	10	0	
2A	25000	23	27.0	42.0	10	0	10 minutes
3A	50000	23	27.0	42.0	10	0	15 minutes
4A	100000	23	27.0	42.0	10	0	15 minutes
5A	100000	23	27.0	42.0	60	0	10 minutes
6A	100000	23	27.0	42.0	300(1)	0	15 minutes

TEST DATA

(1) In addition to 300 seconds of vibration, the static load of 100000 psi was applied for 16 hours.

Material	Specimen Number	Specimen Height, In. Before	Specimen Height, In. After	Specimen Diameter, In. Before	Specimen Diameter, In. After	Hardness Rockwell Before	Hardness Rockwell After	Surface Finish, CLA Before	Surface Finish, CLA After
Ti-6Al-4V	11B	0.973	0.973	0.181	0.181	R_c-37	R_c-37	21	18
Ti-6Al-4V	12E	0.968	0.968	0.460	0.460	R_c-38	R_c-38	24	16

PHYSICAL MEASUREMENTS OF TEST SPECIMENS

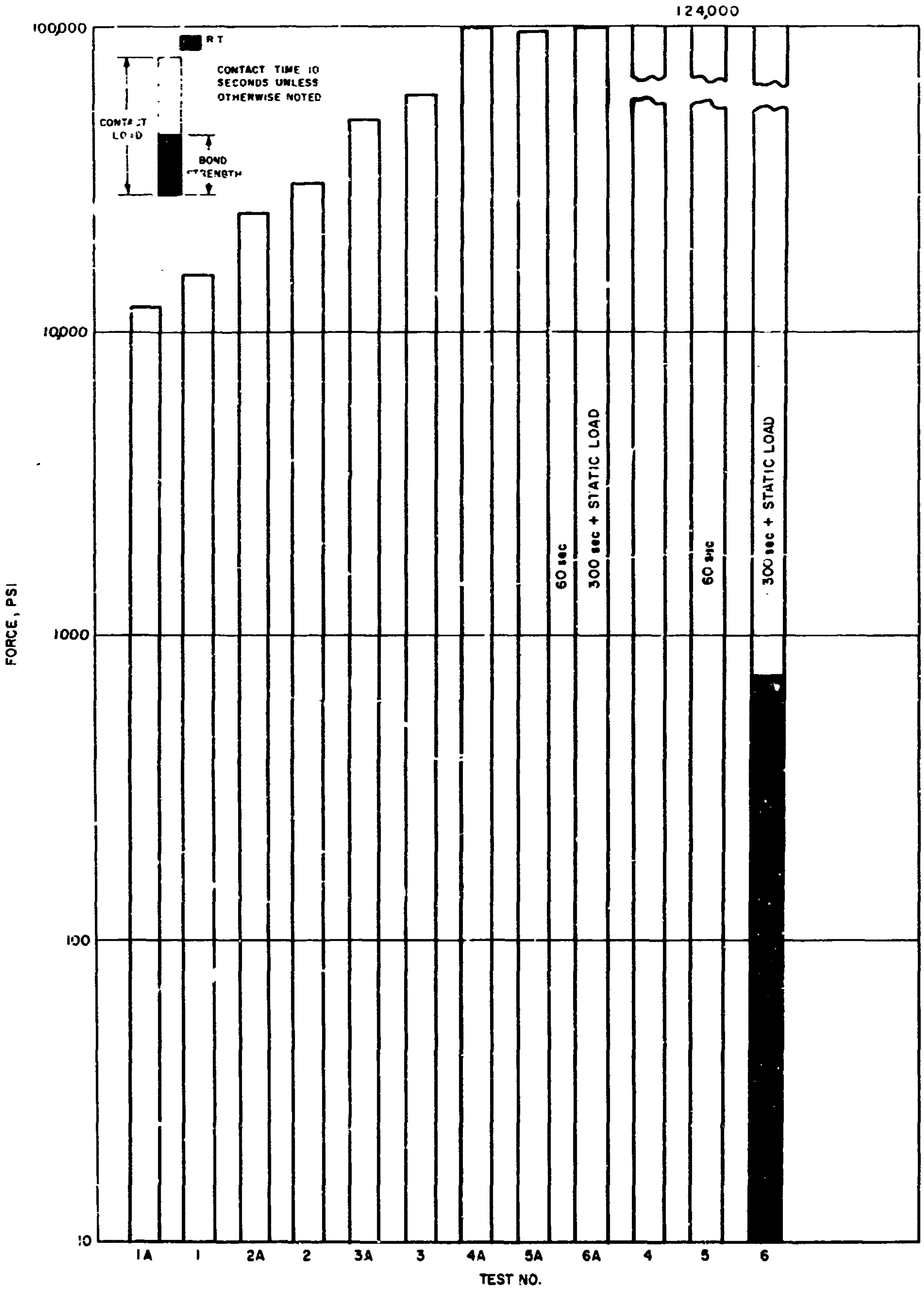


Figure 24. Contact loads versus bond strengths Ti-6Al-4V/Ti-6Al-4V.

TEST RESULTS

FIG. 25
MAGNIFICATION 2.5 x
TOP Copper No. 1A
BOTTOM Copper No. 2A
NEGATIVE NO. 01856P

TOP BOTTOM

Test No.	Axial Load PSI	Temp. °C	Pressure, 10^{-10} Torr Measured Kreisman	Pressure, 10^{-10} Torr Corrected	Time of Vibration Seconds	Bond Strength PSI	Time of Specimen Separation Between Tests
1	930	23	3.2	5.1	10	110	
2	1860	23	4.2	6.8	10	470	25 minutes

TEST DATA

Material	Specimen Number	Specimen Height, In. Before	Specimen Height, In. After	Specimen Diameter, In. Before	Specimen Diameter, In. After	Hardness Rockwell Before	Hardness Rockwell After	Surface Finish, CLA Before	Surface Finish, CLA After
Copper	1A	0.975	0.975	0.360	0.360	15T-54	15T-54	18	34
Copper	2A	0.973	0.973	0.461	0.461	15T-55	15T-55	22	45

PHYSICAL MEASUREMENTS OF TEST SPECIMENS

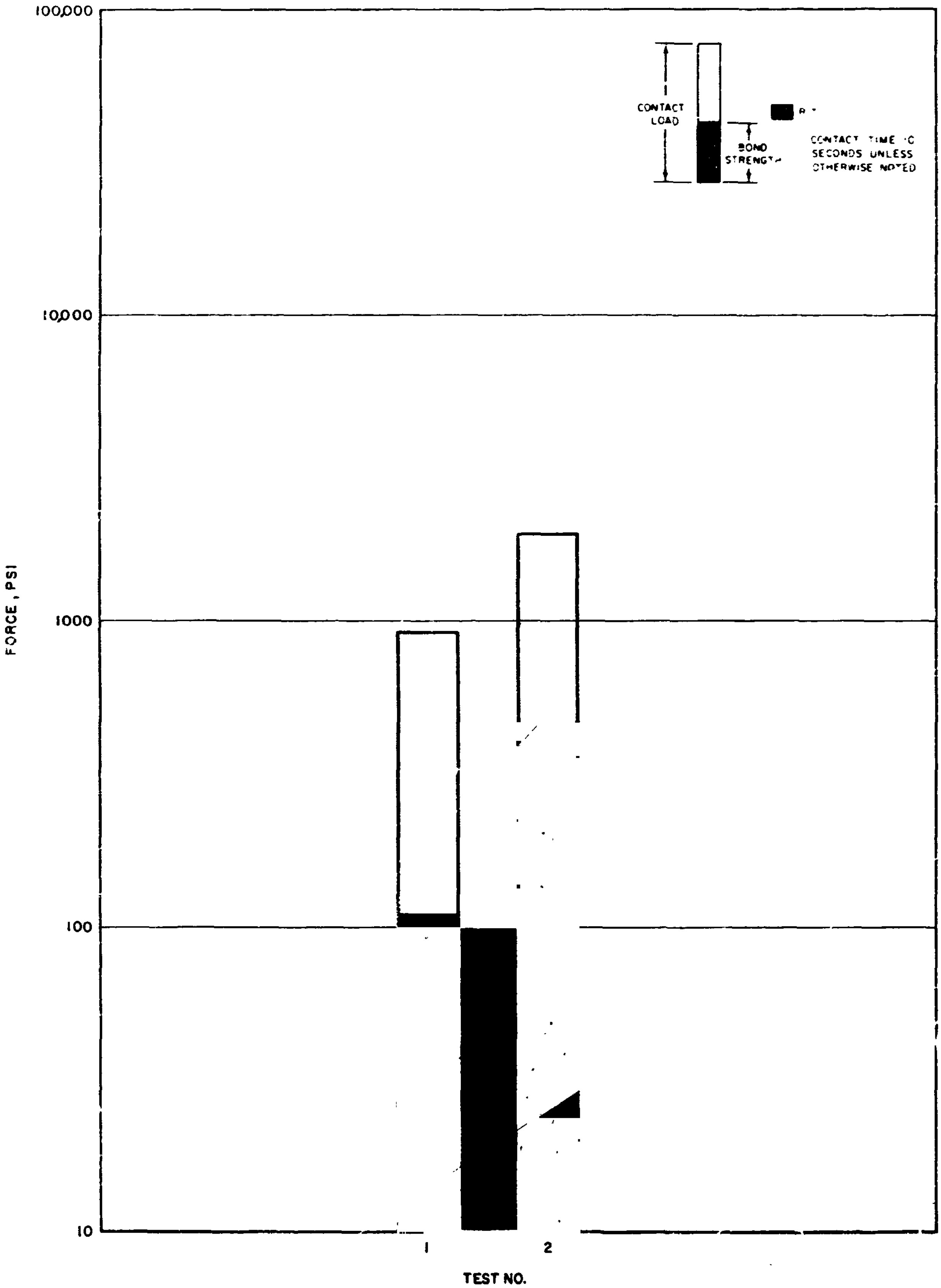


Figure 26. Contact loads versus bond strengths copper/copper.

TEST RESULTS

FIG. 27
MAGNIFICATION 2.5 x
TOP 304 Steel No. 3B
BOTTOM 2014-T6 Aluminum No. 6B
NEGATIVE NO. 01859P

TOP BOTTOM

Test No.	Axial Load PSI	Temp. °C	Pressure, 10^{-10} Torr Measured Kreisman	Pressure, 10^{-10} Torr Corrected	Time of Vibration Seconds	Bond Strength PSI	Time of Specimen Separation Between Tests
1	4350	22.5	1.6	2.6	10	0	
2	8700	22.5	2.5	3.9	10	0	10 minutes
3	17400	22.5	2.2	3.4	10	0	10 minutes
4	34700	22.5	2.4	3.7	10	0	10 minutes
5	34700	22.5	3.6	5.7	60	0	15 minutes
6	34700	22.5	3.8	6.1	60	0	10 minutes
7	34700	22.5	1.6	2.6	300 (1)	0	3 hours 55 minutes
8	3720	150	6.2	11.0	10	0	
9	3720	150	8.0	13.5	10	0	40 minutes
10	7450	150	7.2	12.5	10	0	20 minutes

TEST DATA

(1) In addition to 300 seconds of vibration, the static load of 34700 psi was applied for 19 hours.

Material	Specimen Number	Specimen Height, In. Before	Specimen Height, In. After	Specimen Diameter, In. Before	Specimen Diameter, In. After	Hardness Rockwell Before	Hardness Rockwell After	Surface Finish, CLA Before	Surface Finish, CLA After

PHYSICAL MEASUREMENTS OF TEST SPECIMENS

The upper heater element burned out and the vacuum chamber was disassembled to replace the element after the room temperature test. This accounts for the two different wear patterns on the test specimens because the contact area after reassembly was not the same as the original contact area.

Continued on next page

FIG. 27 (cont)
MAGNIFICATION
TOP
BOTTOM
NEGATIVE NO.

Test No.	Axial Load PSI	Temp. °C	Pressure, 10^{-10} Torr Measured Kreisman	Pressure, 10^{-10} Torr Corrected	Time of Vibration Seconds	Bond Strength PSI	Time of Specimen Separation Between Tests
11	14900	150	9.0	15.5	10	95	15 minutes
12	14900	150	8.0	13.5	10	0	15 minutes
13	29800	150	9.2	20.0	10	0	15 minutes
14	29800	150	6.2	11.0	60	0	10 minutes
15	29800	150	6.2	11.0	60	40	10 minutes
16	29800	150	7.4	12.5	60	0	1 hour 35 minutes
17	29800	150	4.8	7.9	300(1)	0	20 minutes
18	1200	300	48.0	68.0	10	>800(2)	77 hours 20 minutes
19	1000	300	41.0	60.0	10	2420	20 minutes
20	1500	300	29.0	45.0	10	4250	20 minutes

TEST DATA

(1) In addition to 300 seconds of vibration, the static load of 29800 psi was applied for 19 hours.
(2) The recorder for strain measurement was set for high sensitivity and went off scale before the bond broke.

Material	Specimen Number	Specimen Height, In. Before	Specimen Height, In. After	Specimen Diameter, In. Before	Specimen Diameter, In. After	Hardness Rockwell Before	Hardness Rockwell After	Surface Finish, CLA Before	Surface Finish, CLA After
304 Steel	3B	0.973	0.973*	0.255	0.256	30T-78	30T-79	32	70
2014-T6Al	6B	0.973	0.973	0.461	0.461	15T-87	15T-68	28	57

PHYSICAL MEASUREMENTS OF TEST SPECIMENS

*Height in one area of adhesion was 0.980 inches.

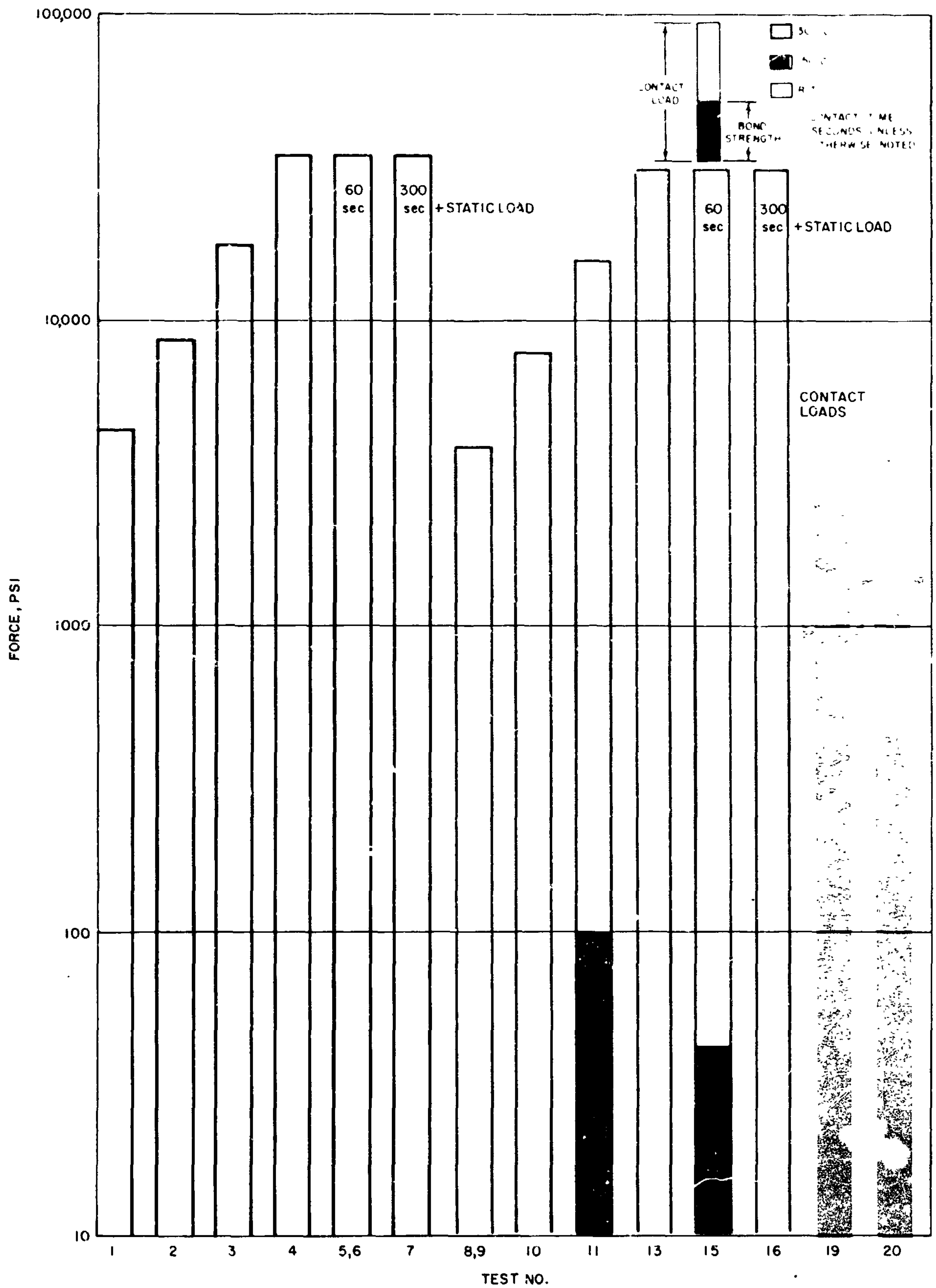


Figure 28. Contact loads versus bond strengths 304 steel/2014-T6 aluminum.

TEST RESULTS

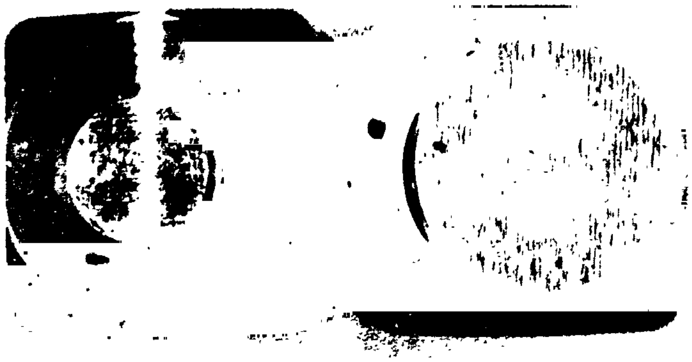


FIG. 29
MAGNIFICATION 2.5 x
TOP 304 Steel No. 3A
BOTTOM Rene' 41 No. 8B
NEGATIVE NO. 01858P

TOP BOTTOM

Test No.	Axial Load PSI	Temp. °C	Pressure, 10^{-10} Torr Measured Kreisman	Pressure, 10^{-10} Torr Corrected	Time of Vibration Seconds	Bond Strength PSI	Time of Specimen Separation Between Tests
1	14000	22.5	1.9	2.9	10	0	
2	28000	22.5	2.4	3.7	10	0	10 minutes
3	28000	22	2.0	3.0	10	0	10 minutes
4	28000	22	1.9	2.9	10	0	15 minutes
5	28000	22.5	2.0	3.0	60	0	10 minutes
6	28000	21.5	2.0	3.0	60	0	25 minutes
7	28000	22.5	1.8	2.8	60	0	35 minutes
8	28000	22.5	1.3	2.3	300 (1)	0	25 minutes
9	3000	150	2.1	3.2	10	0	1 hour 10 minutes
10	6000	150	2.2	3.4	10	100	10 minutes
11	6000	150	3.8	6.1	10	125	10 minutes

TEST DATA

(1) In addition to 300 seconds of vibration, the static load of 28000 psi was applied for 19 hours.

Material	Specimen Number	Specimen Height, In. Before	Specimen Height, In. After	Specimen Diameter, In. Before	Specimen Diameter, In. After	Hardness Rockwell Before	Hardness Rockwell After	Surface Finish, CLA Before	Surface Finish, CLA After
304 Steel	3A	0.972	0.972	0.255	0.255	30T-80	30T-80	32	40
Rene' 41	8B	0.974	0.974	0.461	0.461	R_c-42	R_c-42	21	32

PHYSICAL MEASUREMENTS OF TEST SPECIMENS

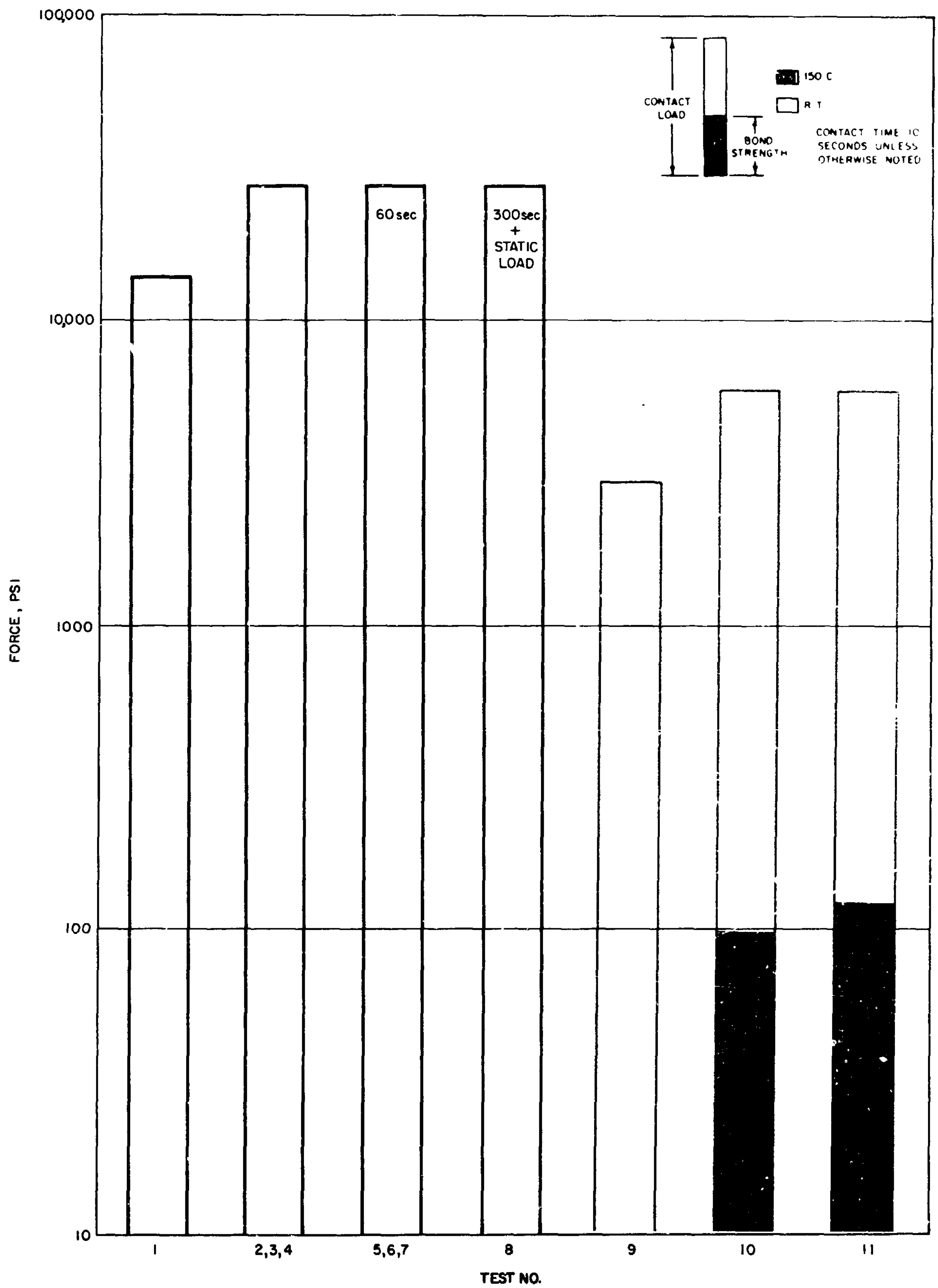


Figure 30. Contact loads versus bond strengths 304 steel/René 41.

TEST RESULTS

FIG. 31
MAGNIFICATION 2.5 x
TOP 2014-T6 Aluminum No. 5D
BOTTOM A 286 Steel No. 10D
NEGATIVE NO. 01938P

TOP BOTTOM

Test No.	Axial Load PSI	Temp. °C	Pressure, 10^{-10} Torr Measured Kreisman	Corrected	Time of Vibration Seconds	Bond Strength PSI	Time of Specimen Separation Between Tests
1	5750	22	2.5	3.9	10	0	
2	11500	22	2.5	3.9	10	0	15 minutes
3	23000	22	3.8	6.1	10	0	15 minutes
4	46000	22	4.0	6.5	10	0	15 minutes
5	46000	22	2.7	4.2	60	0	10 minutes
6	46000	22	2.0	3.0	300(1)	0	2 hours 40 minutes
7	3200	150	14.0	23.5	10	0	6 hours 15 minutes
8	6400	150	13.0	22.0	10	215	10 minutes
9	6400	150	12.0	20.0	10	0	10 minutes
10	12800	150	7.0	12.0	10	0	10 minutes
11	25500	150	10.0	17.0	10	0	15 minutes
12	25500	150	14.0	23.5	60	25	10 minutes

TEST DATA

(1) In addition to 300 seconds of vibration, the static load of 46000 psi was applied for 19 hours.

Material	Specimen Number	Specimen Height, In. Before	After	Specimen Diameter, In. Before	After	Hardness Rockwell Before	After	Surface Finish, CIA Before	After
2014-T6Al	5D	0.975	0.975	0.361	0.361	15T-87	15T-86	24	32
A 286	10D	0.975	0.975	0.461	0.461	R_c-35	R_c-35	32	30

PHYSICAL MEASUREMENTS OF TEST SPECIMENS

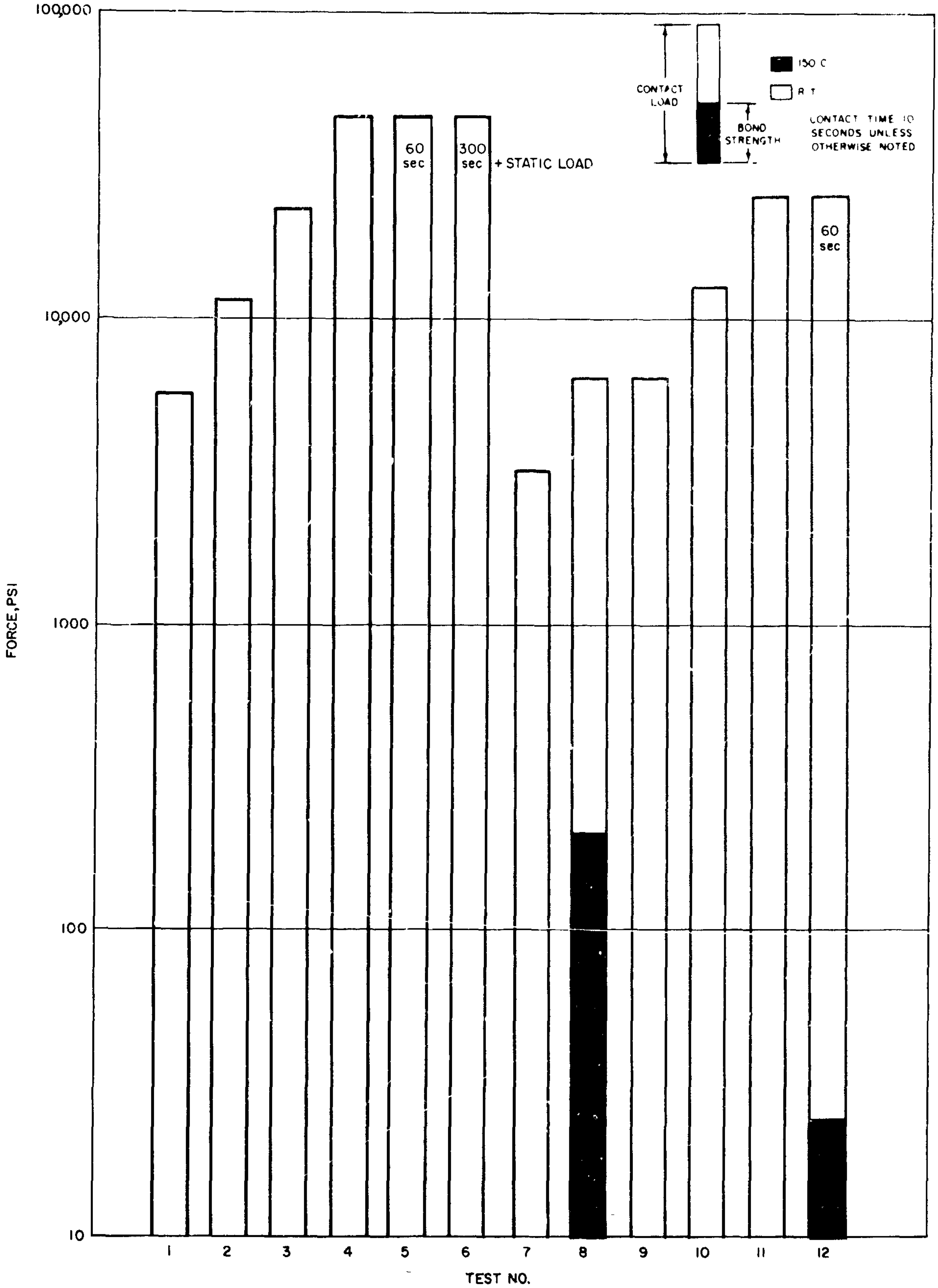
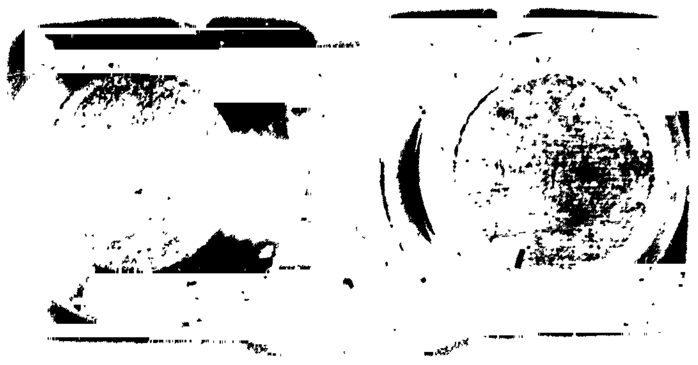


Figure 32. Contact loads versus bond strengths 2014-T6 aluminum A286 steel.



TEST RESULTS

FIG. 33
MAGNIFICATION 2.5 x
TOP 2014-T6 Aluminum No. 5B
BOTTOM Rene' 41 No. 8C
NEGATIVE NO. 01861P

TOP BOTTOM

Test No.	Axial Load PSI	Temp. °C	Pressure, 10^{-10} Torr Measured Kreisman	Pressure, 10^{-10} Torr Corrected	Time of Vibration Seconds	Bond Strength PSI	Time of Specimen Separation Between Tests
1	5750	22	2.2	3.4	10	0	
2	11500	22	2.5	3.9	10	0	20 minutes
3	23000	22	2.4	3.7	10	0	30 minutes
4	46000	22	2.2	3.4	10	0	20 minutes
5	46000	22	2.4	3.7	60	0	10 minutes
6	46000	22	2.8	4.4	300	0	20 minutes
7	3190	150	11.0	18.5	10	55	21 hours 24 minutes
8	3190	150	14.0	23.5	10	325,195(1)	20 minutes
9	6380	150	14.0	23.5	10	200,110,10(1)	25 minutes
10	12750	150	6.0	10.0	10	15	25 minutes
11	12750	150	8.0	13.5	10	45	25 minutes
12	12750	150	15.0	25.0	10	0	10 minutes

TEST DATA

(1) Multiple tensile forces were recorded in breaking of the bond.

Material	Specimen Number	Specimen Height, In. Before	After	Specimen Diameter, In. Before	After	Hardness Rockwell Before	After	Surface Finish, CLA Before	After
2014-T6Al	5B	0.973	0.973	0.361	0.361	15T-86	15T-83*	24	33
Rene' 41	8C	0.973	0.975	0.460	0.460	R_C-43	R_C-43	25	28

PHYSICAL MEASUREMENTS OF TEST SPECIMENS

*Specimen was softened slightly by temperature from bake out, but yield strength was not exceeded.

TOP BOTTOM

FIG. 34
MAGNIFICATION 2 x
TOP Rene' 41 No. 7C
BOTTOM 2014 Aluminum No 6D
NEGATIVE NO. 01941P

Test No.	Axial Load PSI	Temp. °C	Pressure, 10^{-10} Torr Measured Kreisman	Corrected	Time of Vibration Seconds	Bond Strength PSI	Time of Specimen Separation Between Tests
1A	5750	21.5	13.0	22.0	10	0	
2A	11500	21.5	17.0	29.0	10	0	10 minutes
3A	23000	21.5	15.0	25.0	10	0	10 minutes
4A	46000	21.5	15.0	25.0	10	0	10 minutes
5A	46000	21.5	17.0	29.0	60	0	10 minutes
6A	46000	21.5	17.0	29.0	300	0(1)	10 minutes
7A	3200	150	30.0	46.0	10	0	3 hours 15 minutes
8A	6375	150	26.0	41.0	10	0(1)	10 minutes
9A	12750	150	26.0	41.0	10	0(1)	10 minutes
10A	25500	150	26.0	41.0	10	0	10 minutes

TEST DATA

(1) Before the compressive load was completely removed there was an audible indication and a pressure "pip" on the strain recorder indicating a sudden relief of stresses.

Material	Specimen Number	Specimen Height, In. Before	After	Specimen Diameter, In. Before	After	Hardness Rockwell Before	After	Surface Finish, CLA Before	After
Rene' 41	7C	0.975	0.975	0.182	0.182	R_c-43	R_c-43	20	26
2014-Al	6D	0.972	0.972	0.461	0.461	15T-87	15T-85	23	36

PHYSICAL MEASUREMENTS OF TEST SPECIMENS

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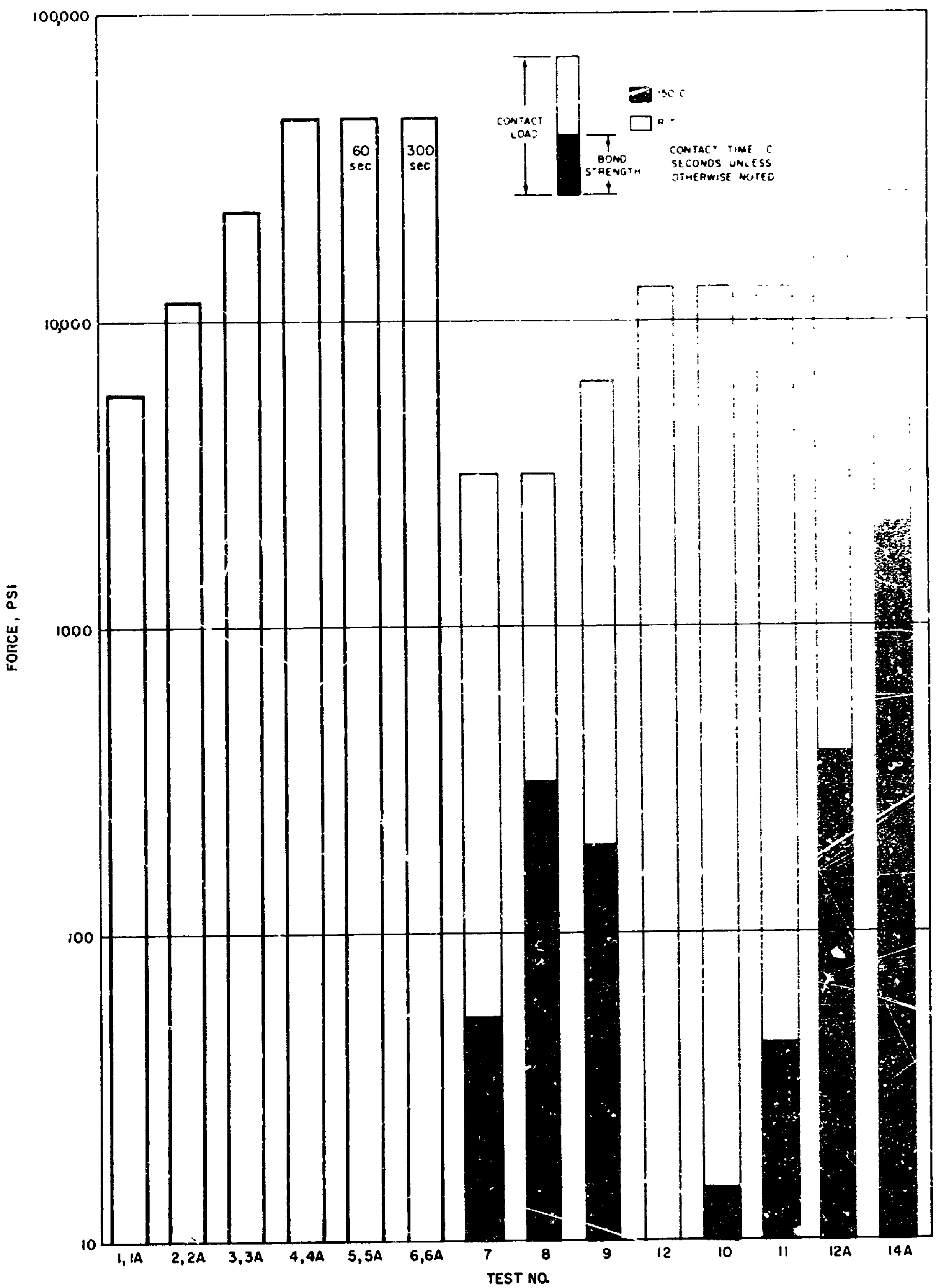

Figure 35. Contact loads versus bond strengths 2014-T6 aluminum/René 41.

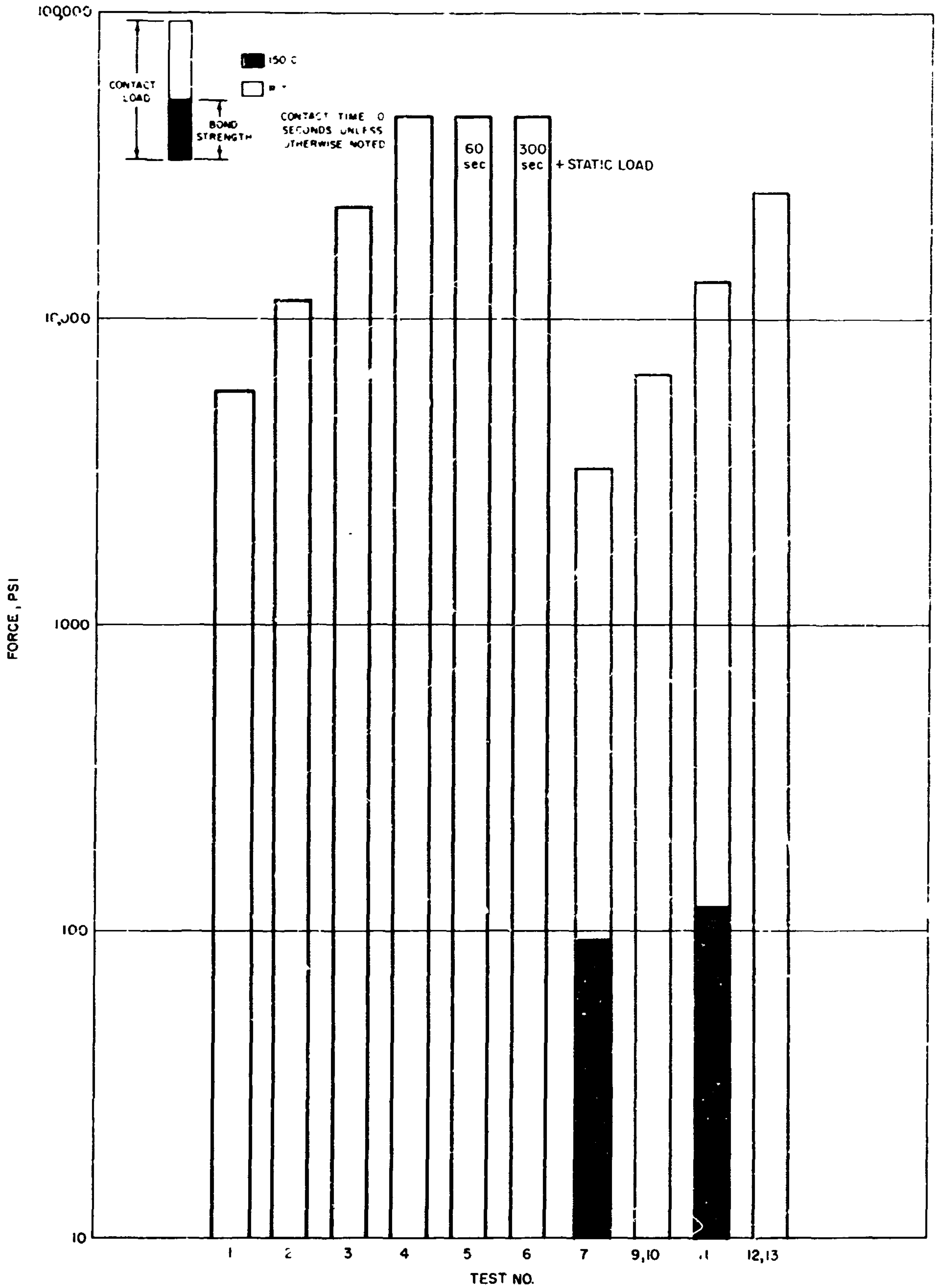

Figure 37. Contact loads versus bond strengths 2014-T6 aluminum/Ti-6Al-4V.

METALLOGRAPHIC EXAMINATION

Selected photomicrographs of cross sections taken through the contact surfaces of the test specimens are presented in Figures 38 through 46. In Figure 38, the surface outside of the contact area of a 304 steel specimen from a 304 steel to 304 steel couple is shown. The contact area shown in Figure 39 shows that metal from the mating specimen has "plowed" into and bonded to specimen no. 4D. The microstructure shows evidence of cold working from the loads applied in testing.

Figure 40 compares the surface outside of the contact area with the contact surface in Figure 41 of a 2014 aluminum specimen from a 2014 aluminum to 2014 aluminum couple. Metal from the mating specimen can be seen cohering to the specimen shown in Figure 41.

The surface conditions of copper in a copper to copper couple in a non-contact area and in the bonded areas after breaking of the bond are compared in Figures 42, 43, and 44. In Figure 43 roughening of the surface and sticking of metal from the mating specimen is evident. Figure 44 shows a protuberance that appears to be elongation at a localized area resulting from tensile forces applied when the bond was broken.

Figure 45 is the non-contact area of a 304 steel specimen which was tested in a 304 steel to Rene' 41 couple. The bonding area shown in Figure 46 shows a general roughening of the surface. Foreign particles 0.0007 inches beneath the contact surfaces are evident. This condition may have been present in the raw material, but it was not found in other areas of the specimen.

Figure 38. 304 steel specimen 4D showing original surface.
Magnification: 1000X
Etchant: marbles
Couple: 304 steel to 304 steel
Surf ce appearance shown in Figure 13
Negative No. 01872

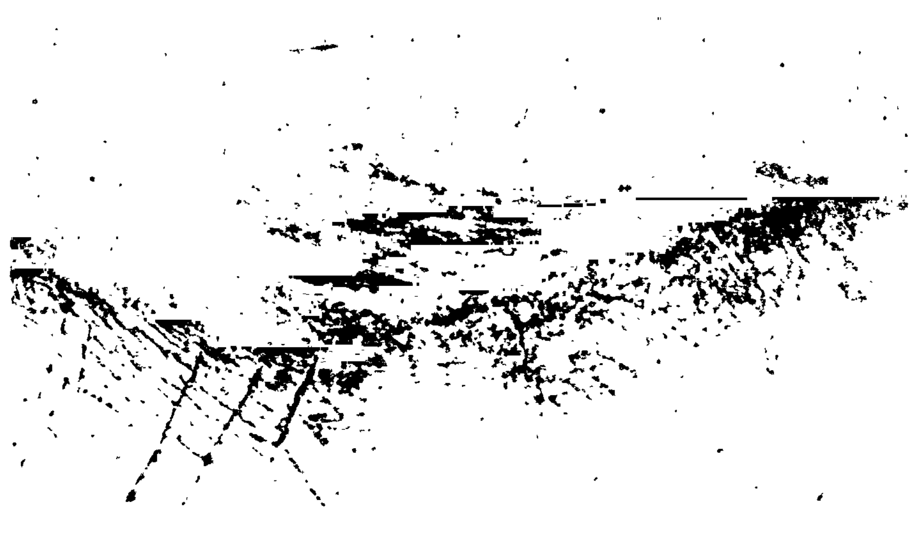

Figure 39. 304 steel specimen No. 4D showing area of bonding.
Magnification: 1000X
Etchant: marbles
Couple: 304 steel to 304 steel
Load: 7000 psi for 10 sec. oscillation
Temperature: 22C
Bond strength: 360 psi
Surface appearance shown in Figure 13
Negative No. 01873

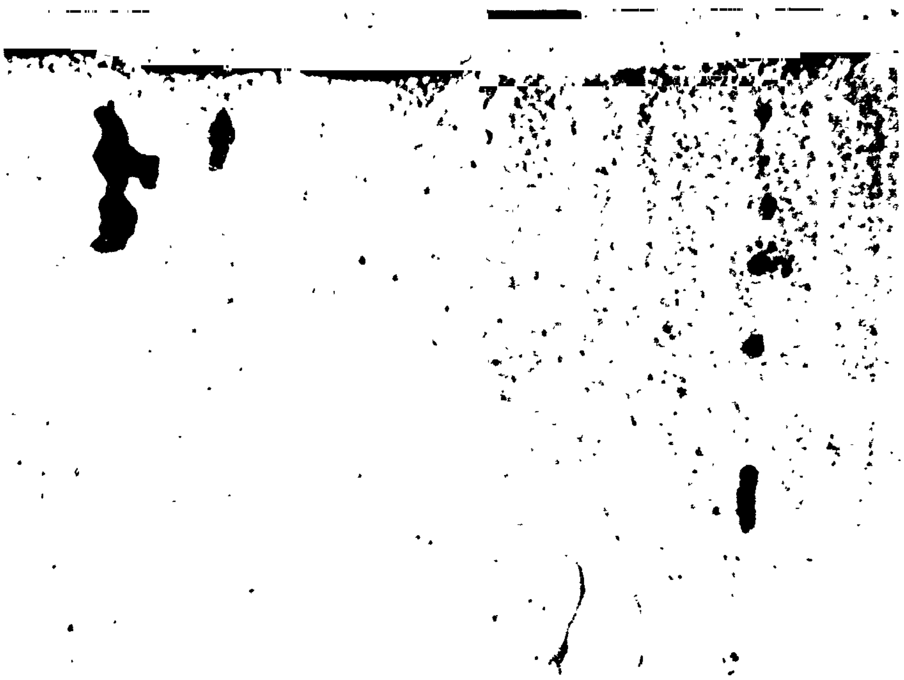

Figure 40. 2014 aluminum specimen No. 6A showing original surface.
Magnification: 1000X
Etchant: Keller's etch
Couple: 2014 aluminum to 2014 aluminum
Surface appearance shown in Figure 15
Negative No. 01876

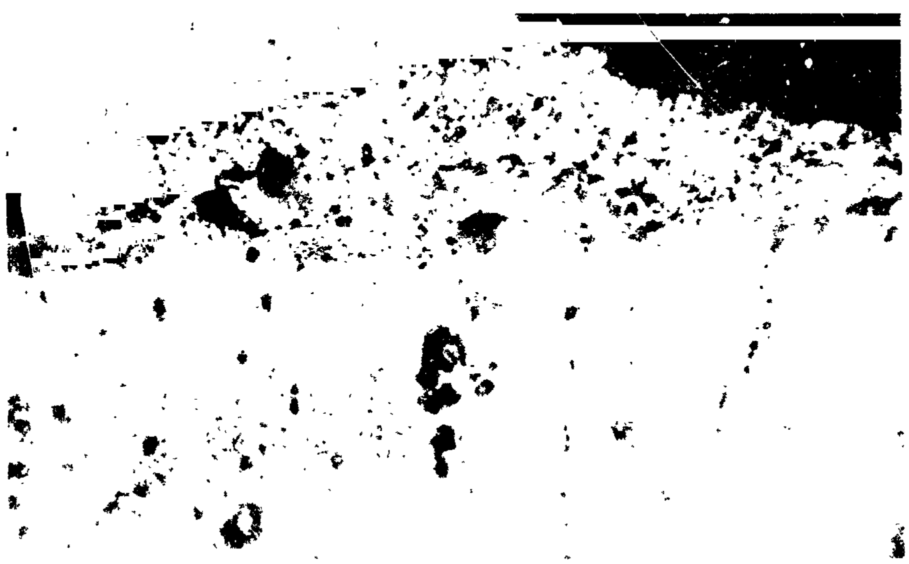

Figure 41. 2014 aluminum specimen No. 6A showing area of bonding.
Magnification: 1000X
Etchant: Keller's etch
Couple: 2014 aluminum to 2014 aluminum
Load: 3190 psi for 10 sec. oscillation
Temperature: 150C
Bond strength: 2420 psi
Negative No. 01877

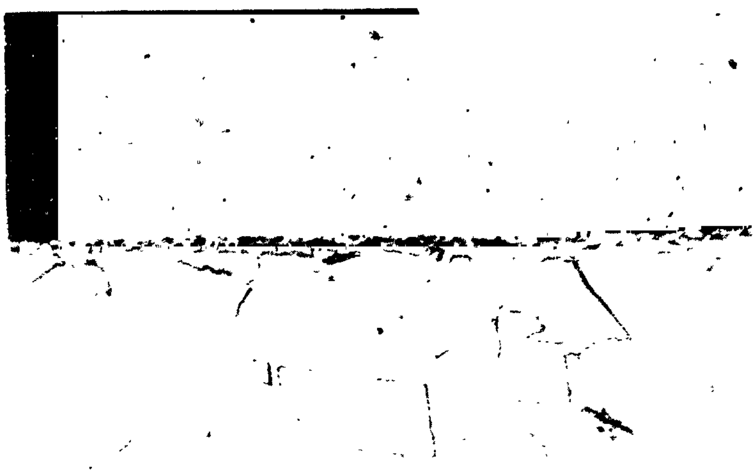

Figure 42. Copper specimen No. 2A showing original surface.
Magnification: 500X
Etchant: potassium dichromate
Couple: copper to copper
Surface appearance shown in Figure 25
Negative No. 01874

Figure 43. Copper specimen No. 2A showing area of bonding.
Magnification: 500X
Etchant: potassium dichromate
Couple: copper to copper
Load: 1860 psi for 10 sec. oscillation
Temperature: 23C
Bond strength: 470 psi
Negative No. 01875

Figure 44. Copper specimen No. 2A showing area of bonding.
Magnification: 1000X
Etchant: potassium dichromate
See previous figure for test data.
Negative No. 01940

Figure 45. 304 steel specimen No. 3A showing original surface.
Magnification: 500X
Etchant: none
Couple: 304 steel to René 41
Surface appearance shown in Figure 29
Negative No. 01878

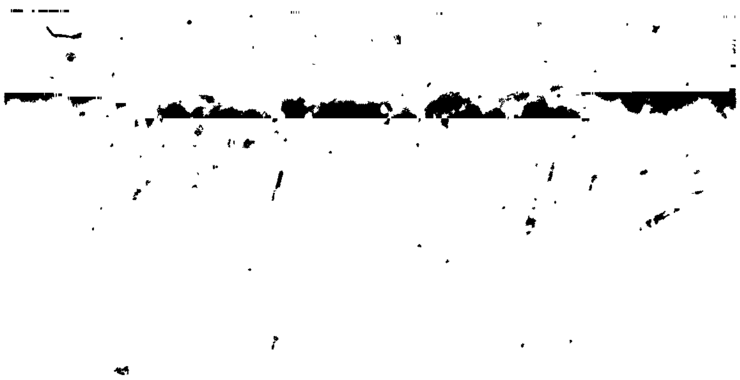

Figure 46. 304 steel specimen No. 3A showing area of bonding.
Magnification: 1000X
Etchant: none
Couple: 304 steel to Rene' 41
Load: 6000 psi for 10 sec. oscillation
Temperature: 150C
Bond strength: 125 psi
Negative No. 01879

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IX. SUMMARY

STATIC TESTS

The results of the static tests of reference 1 and those conducted during the second year of the program are summarized in Figure 47.

It is shown that the harder materials were not subject to adhesion or cohesion under the static test conditions of maximum severity. The material combinations in this category were:

(1) 304 steel/304 steel
(2) 304 steel/A286 steel
(3) 304 steel/6Al-4V-titanium
(4) 304 steel/Rene' 41
(5) 6Al-4V-titanium/6Al-4V-titanium
(6) 6Al-4V-titanium/Rene' 41
(7) A286 steel/A286 steel
(8) A286 steel/Rene' 41
(9) Rene'41/Rene' 41
(10) 17-4PH steel/17-4PH steel

It is assumed that those material combinations which did not bond at a temperature of 500C will not adhere or cohere at lower temperatures. Therefore those material couples should be suitable for static loading conditions in the space environment when loaded within their elastic limits at temperatures up to and including 500C.

No cohesion or adhesion of the following couples occurred at 150C, but most of them bonded at 300C:

(1) Copper/Copper
(2) 2014 aluminum/2014 aluminum
(3) 2014 aluminum/304 steel
(4) 2014 aluminum/A286 steel
(5) 2014 aluminum/Rene' 41
(6) 2014 aluminum/6Al-4V-titanium

The latter material combination did not adhere when loaded within the elastic limit of the aluminum alloy. Considering the tendency of the aluminum alloy to adhere to every other alloy tested at 300C,

FIG. 34 (cont)
MAGNIFICATION
TOP
BOTTOM
NEGATIVE NO.

Test No.	Axial Load PSI	Temp. °C	Pressure, 10^{-10} Torr Measured Kreisman	Corrected	Time of Vibration Seconds	Bond Strength PSI	Time of Specimen Separation Between Tests
11A	25500	150	26.0	41.0	60	0 (1)	10 minutes
12A	25500	150	27.0	42.0	60	400	10 minutes
13A	25500	150	28.0	44.0	300	>830 (2)	10 minutes
14A	25500	150	27.0	42.0	300	2160	20 minutes

TEST DATA

(1) Before the compressive load was completely removed there was an audible indication and a pressure "pip" on the strain recorder indicating a sudden relief of stresses.

Material	Specimen Number	Specimen Height, In. Before	Specimen Height, In. After	Specimen Diameter, In. Before	Specimen Diameter, In. After	Hardness Rockwell Before	Hardness Rockwell After	Surface Finish, CIA Before	Surface Finish, CIA After

PHYSICAL MEASUREMENTS OF TEST SPECIMENS

(2) The strain recorder was set on too sensitive a scale to measure the total stress.

TEST RESULTS

FIG.	36
MAGNIFICATION	215 x
TOP	2014-T6 Aluminum No. 5E
BOTTOM	Ti6Al-4V No. 12C
NEGATIVE NO.	01939P

TOP BOTTOM

Test No.	Axial Load PSI	Temp. °C	Pressure, 10^{-10} Torr Measured Kreisman	Corrected	Time of Vibration Seconds	Bond Strength PSI	Time of Specimen Separation Between Tests
1	5750	22	19.0	32.0	10	0	
2	11500	22	18.0	30.0	10	0	15 minutes
3	23000	22	10.0	17.0	10	0	15 minutes
4	46000	22	16.0	27.0	10	0	10 minutes
5	46000	23	15.0	25.0	60	0	1 hour 20 minutes
6	46000	23	6.4	11.0	300 (1)	0	15 minutes
7	3200	150	22.0	36.0	10	95	4 hours 25 minutes
8	3200	150	22.0	36.0	10	35	20 minutes
9	6400	150	21.0	34.5	10	0	15 minutes
10	6400	150	19.0	15.5	10	0	20 minutes
11	12750	150	28.0	44.0	10	120	10 minutes
12	25500	150	19.0	32.0	10	0	15 minutes
13	25500	150	19.0	32.0	10	0	15 minutes

TEST DATA

(1)

Material	Specimen Number	Specimen Height, In. Before	After	Specimen Diameter, In. Before	After	Hardness Rockwell Before	After	Surface Finish, CIA Before	After
2014-T6Al	5E	0.975	0.975	0.361	0.361	15T-87	15T-85	30	43
Ti6Al-4V	12C	0.975	0.975	0.460	0.460	R_C-38	R_C-37	20	18

PHYSICAL MEASUREMENTS OF TEST SPECIMENS

COUPLE	BOND STRENGTH, PSI (1000 / 2000)	TEST CONDITIONS: TEMP, °C	TEST CONDITIONS: LOAD, PSI	TEST CONDITIONS: TIME, SEC	REMARKS
COPPER TO COPPER		150	5600	≤ 70,000	
		300	1800	≤ 10,000	
	160	300	1800	70,000	
	30	500	800	10	SUCCESSIVE TESTS OF SAME COUPLE
	170	500	800	100	
	1170	500	800	70,000	
2014Al TO 2014Al		150	64,500	≤ 70,000	CREEP STRENGTH EXCEEDED
		300	1410	≤ 70,000	
		300	2200	≤ 10,000	
	850	300	2950	70,000	
2014Al TO 304 STEEL		150	25,500	≤ 70,000	
		300	2940	≤ 10,000	
	455	300	2550	70,000	
2014Al TO A286 STEEL		150	25,500	≤ 70,000	
		300	3440	≤ 10,000	
	80	300	3150	10,000	
2014Al TO Ti-6Al-4V		150	25,500	≤ 70,000	
		300	3800	≤ 10,000	
	1785	300	4050	70,000	CREEP STRENGTH EXCEEDED
		300	3440	70,000	
2014Al TO RENE' 41		150	25,500	≤ 70,000	
		300	2500	≤ 10,000	
	1750	300	3220	70,000	
304 STEEL TO 304 STEEL		500	16,000	≤ 70,000	
304 STEEL TO A286 STEEL		500	16,000	≤ 70,000	
304 STEEL TO Ti-6Al-4V		500	16,000	≤ 70,000	
304 STEEL TO RENE' 41		500	16,000	≤ 70,000	
Ti-6Al-4V TO Ti-6Al-4V		150	80,500	≤ 70,000	
		300	69,000	≤ 70,000	
		500	29,000	≤ 70,000	CREEP STRENGTH EXCEEDED
Ti-6Al-4V TO RENE' 41		500	58,000	≤ 1000	
		375	58,000	≤ 70,000	
A286 STEEL TO A286 STEEL		500	67,000	≤ 70,000	
A286 STEEL TO RENE' 41		500	67,000	≤ 70,000	
RENE' 41 TO RENE' 41		500	100,000	≤ 70,000	
17-4PH STEEL TO 17-4PH STEEL		500	65,800	≤ 70,000	

Figure 47. Summary of static adhesion and cohesion tests.

it is recommended that this couple as well as the others listed above be avoided at this temperature in a space environment. Limited tests showed aluminum bonds to itself at 300C even though not in a vacuum. However, those couples are satisfactory for use at 150C or below.

DYNAMIC TESTS

The conditions under which adhesion or cohesion occurred in the dynamic tests and the resultant bond strengths are summarized in Figure 48. Figure 49 compares the test conditions of maximum severity which resulted in no bonding with the minimum test conditions which gave bonding. This summary assumes that loads above the threshhold of bonding will give bonding although not all tests substantiated this.

All material combinations bonded at test conditions within the prescribed parameters and at less severe conditions of time, temperatures, and load than were necessary to obtain adhesion in the static tests. A number of the combinations that did not bond in static tests at 500C readily adhered at room temperature in the dynamic tests. The aluminum alloy which adhered to most other metals and to itself in static tests at 300C did not adhere in room temperature dynamic tests. A temperature of 150C was required before the aluminum alloy would adhere in these tests.

The 2014 aluminum alloy and its couples and the 6Al-4V-titanium alloy were found to be the most resistant to adhesion under dynamic loading. The reason for this may be that their oxide films, which act as barriers to impede the metal-to-metal contact necessary for adhesion, are more resistant to removal by the abrasive action of the faying surfaces than are the films of the other alloys. On the other hand, the ease with which the 2014 aluminum adhered (compared with other alloys) at 300C in the static tests may be due to diffusion of its oxide into the metal to denude the surface of barrier films.

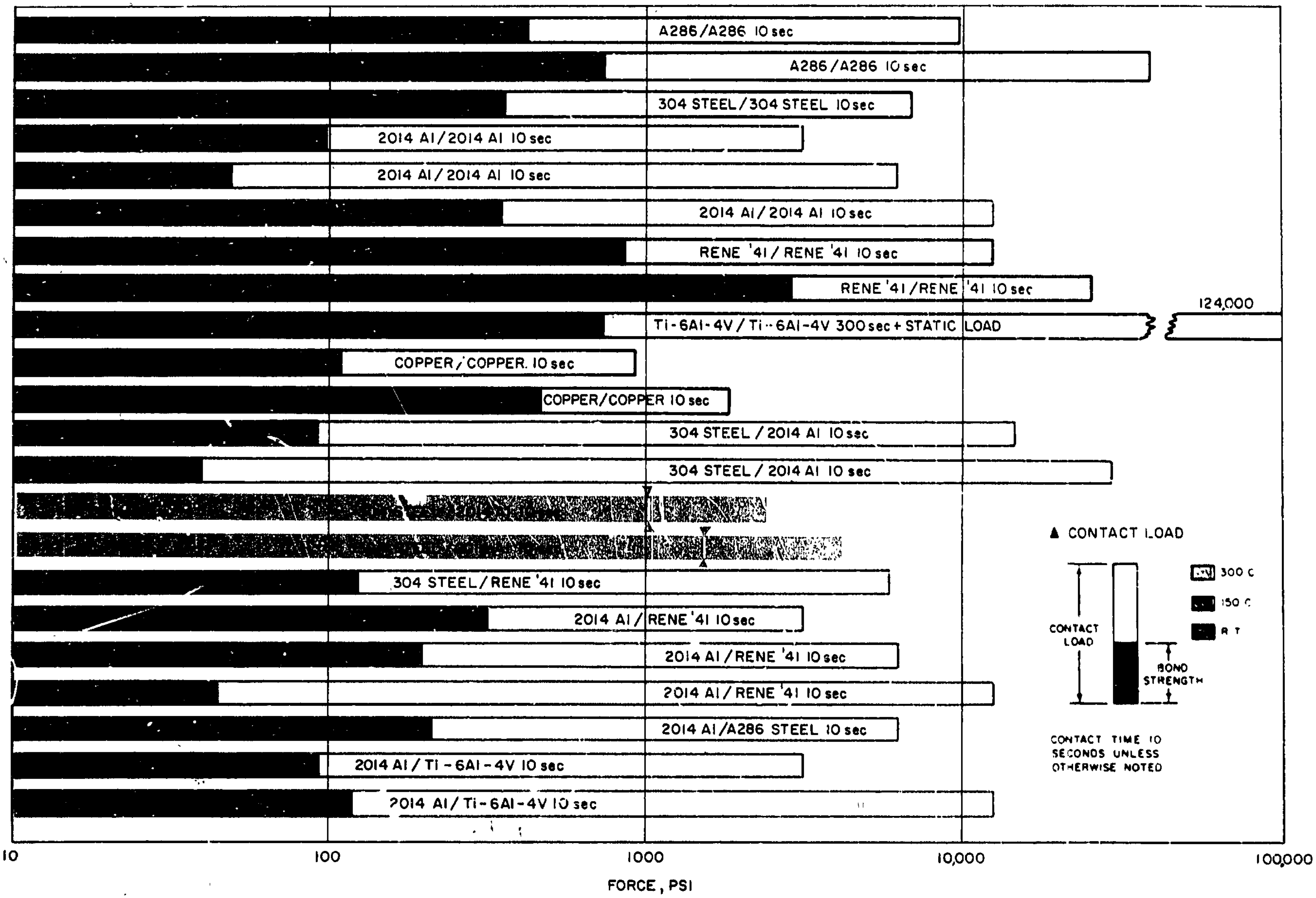

Figure 48. Bond strength of couples tested dynamically.

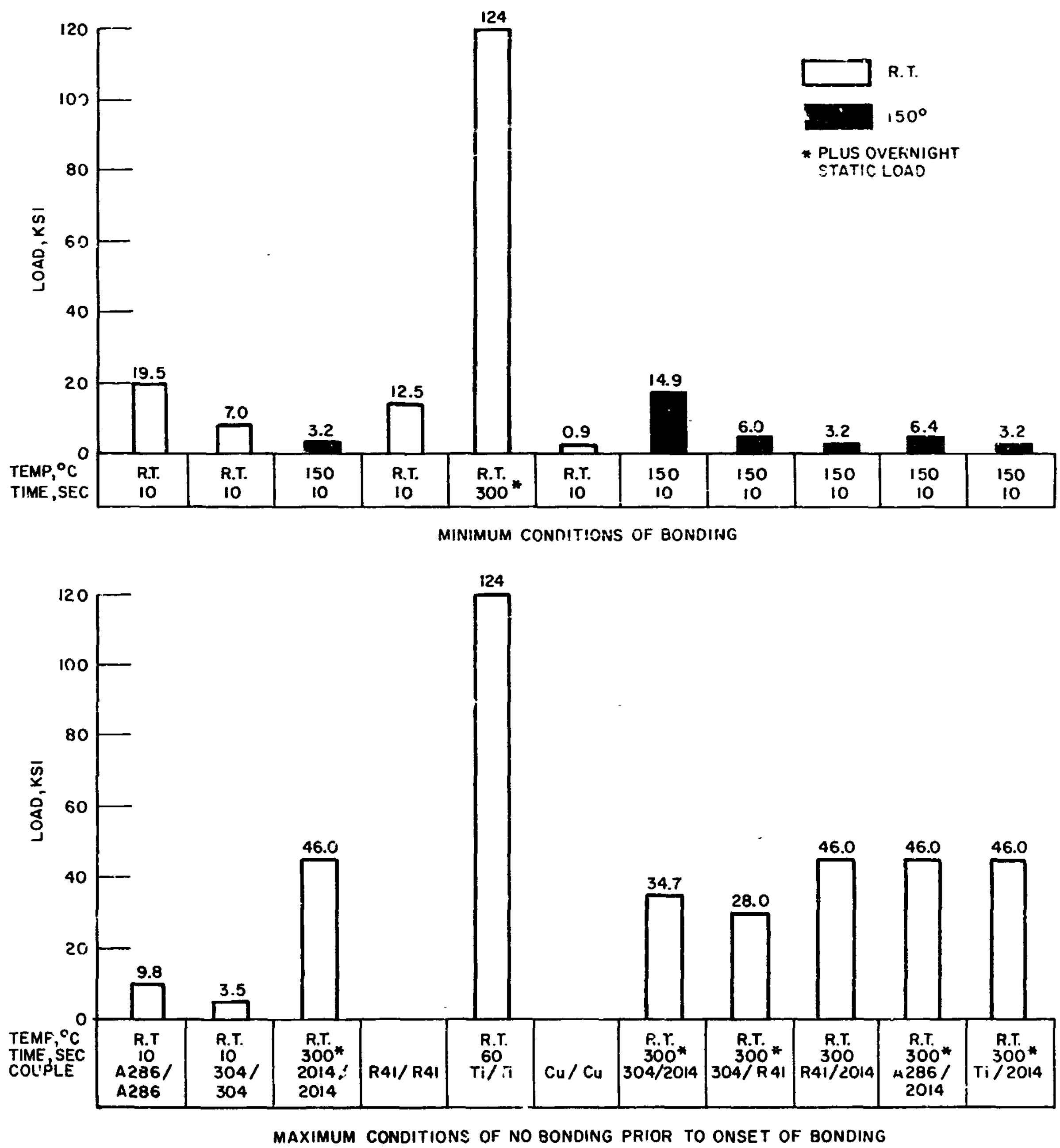

Figure 49. Bonding of metals under dynamic loading.

The copper to copper couple behaved in a predictable manner in that it was the easiest combination to obtain cohesion in both the static and dynamic tests.

In most cases, like metal couples bonded more readily than unlike metal couples. In a paper by Sikorski[3], in which he related coefficients of adhesion of metals in air with various physical and mechanical properties of the metals, he reports lower coefficients of bonding for unlike metal combinations than for like metal combinations. Bowden and Tabor [4] also point out that in removing the normal load, the release of elastic stresses in the material surrounding adhering junctions may pull the junctions apart so that practically no junctions are left when the adhesion measurements are made.

Certain anomalies are shown in the data for some of the material combinations in that adhesion was obtained at relatively low loads, but not at higher loads. This phenomenan was usually with unlike metal couples. An explanation of these anomalies is that shear forces acting on the bonded specimens during elastic relaxation upon release of the compressive load rupture the bonds if they are weak. If this happens, the bond is broken before its strength can be measured. The magnitude of the shear forces is proportional to the applied loads. The shear forces are increased when two materials of dissimilar moduli of elasticity make up the test couple because the material with the lower modulus undergoes more elastic deformation than the other. While these shear forces are modest, it is conceivable that they could disrupt bonds that are weak. If test conditions were of a severity to form a strong bond, it is not likely that the bonds would have been affected by the shear forces accompanied by the elastic relaxation.

As a criteria for use of these couples under dynamic loading, it is recommended that couples that bonded under any load at a given temperature should be avoided in the space environment. Accordingly, the couples tested are rated in Table V in terms of suitability for avoiding bonding in the space environment when loaded within their elastic limits.

No.	Couple	Conditions for Non-Bonding	Conditions for Bonding
1	Copper/Copper		25C and above
2	304 Steel/304 Steel		25C and above
3	2014 Aluminum/ 2014 Aluminum	25C and below	150C and above
4	2014 Aluminum/ 304 Steel	25C and below	150C and above
5	Rene' 41/Rene' 41		25C and above
6	Rene' 41/ 2014 Aluminum	25C and below	150C and above
7	Rene' 41/304 Steel	25C and below	150C and above
8	A286 Steel/A286 Steel		25C and above
9	A286 Steel/ 2014 Aluminum	25C and below	150C and above
10	6Al-4V-Ti/6Al-4V-Ti		25C and above
11	6Al-4V-Ti/2014 Al	25C and below	150C and above

Table V. Temperature limits for avoiding bonding.

COMPARISON BETWEEN STATIC AND DYNAMIC TESTS

Figure 50 compares the static with the dynamic tests in terms of temperatures at which adhesion or cohesion may be expected. Bonding is assumed to occur at temperatures above the lowest temperature at which bonding was observed. Likewise, it is assumed that no bonding will occur at temperatures below the lowest test temperature at which bonding failed to occur.

From the relative ease with which the couples bonded in the dynamic tests, it is concluded that the mechanical abrasion of the rubbing surfaces is effective in removing the barrier films from the surfaces. This affords metal-to-metal contact which sets up the conditions for bonding.

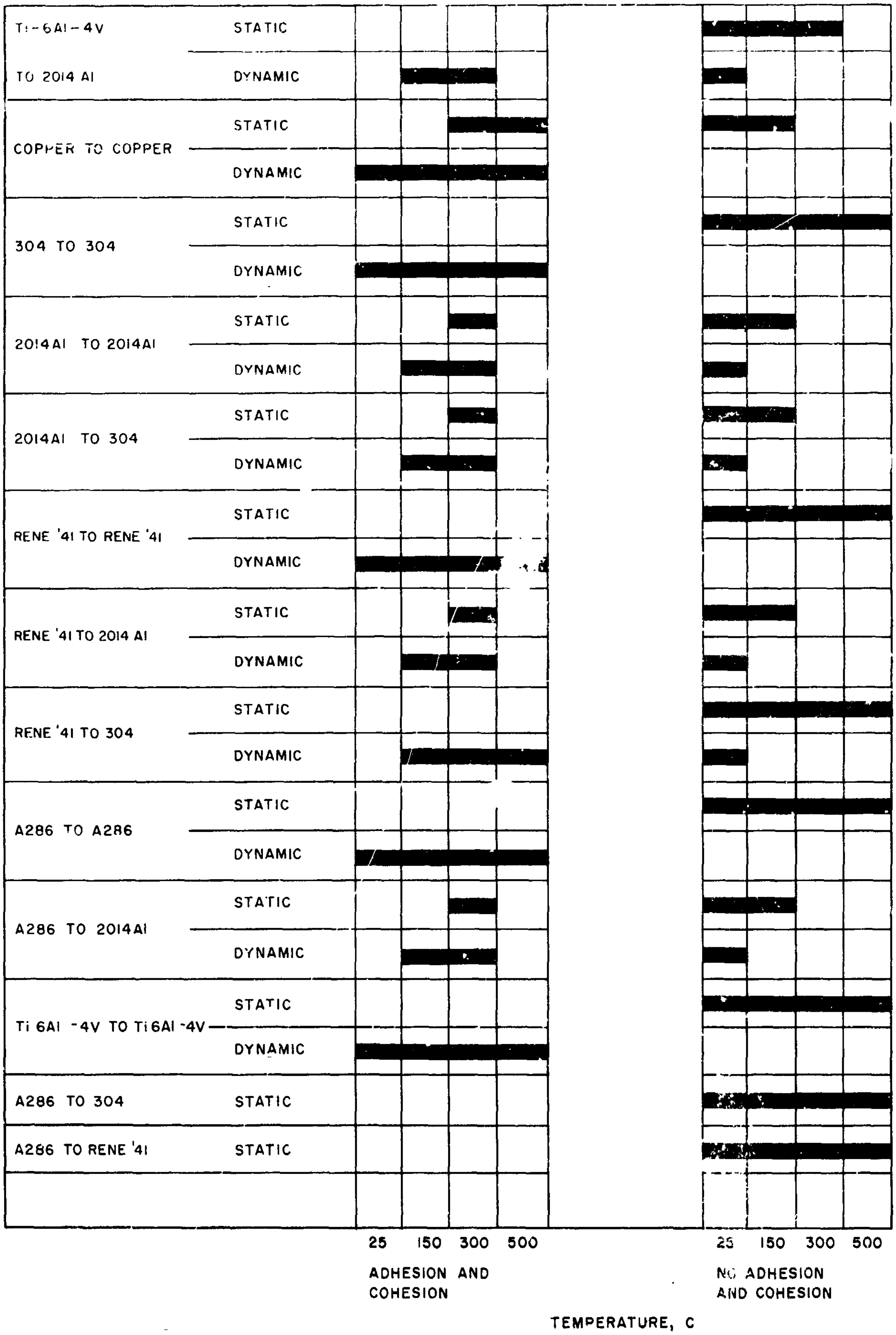

Figure 50. Comparison of adhesion and cohesion under static and dynamic conditions at various temperatures.

Considering the higher loads and temperatures required to obtain bonding under static conditions, it is also evident that the barrier films are not too readily disrupted under static loads. The harder materials, such as stainless steels, super-alloys and titanium alloys, did not bond under the most severe static test conditions. The copper and aluminum alloy couples required higher temperatures for static than for dynamic bonding. Considering the longer time periods and higher temperatures necessary for static bonding, it is probably that diffusion of the oxides into the metals provides a mechanism for partial disruption of the barrier films. Also, even though the bulk yield strength of the materials is not exceeded, localized yielding of surface asperities at higher temperatures may cause breaking up of the barrier films and thus provide increased metal-to-metal contact.

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X. RECOMMENDED FUTURE WORK

Having determined the conditions that promote bonding, the next logical step is to investigate methods to prevent bonding. Among such methods are (1) barrier coatings that will prevent the metallic surfaces from coming in contact, and (2) metallic coatings or alloys that have theoretically low coefficients of adhesion by virtue of their lattice structure, physical properties, or limited solubility in each other.

Included in the first category are ceramic coatings, anodized coatings, flame sprayed ceramic coatings, and anti-friction coatings such as molybdenum disulfide. In the second category are materials having high values of hardness, modulus of elasticity, surface energy, recrystallization temperature, and resistance to plastic flow. Sikorski[3] has defined the various physical and mechanical properties that affect the coefficient of adhesion of metals. Metals having a hexagonal close packed lattice structure have been found to have greater resistance to plastic flow and consequently lower coefficients of adhesion than face centered cubic or body centered cubic structures. Also, study of phase diagrams and atomic diameters serves as an indication of whether two metals are soluble in each other and would tend to weld together by the diffusion process. From these considerations, numerous candidate metals can be selected that should lessen the tendency toward bonding of mating surfaces in space.

The existing special test equipment can be used without modification, to test the effectiveness of barrier coatings on new alloy couples, enabling direct comparisons to be made with the data previously generated for the untreated materials.

The same test equipment can be used to evaluate the bonding properties of new low-adhesion metallic coatings and alloys.

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XI. REFERFNCES

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XII. ACKNOWLEDGEMENTS

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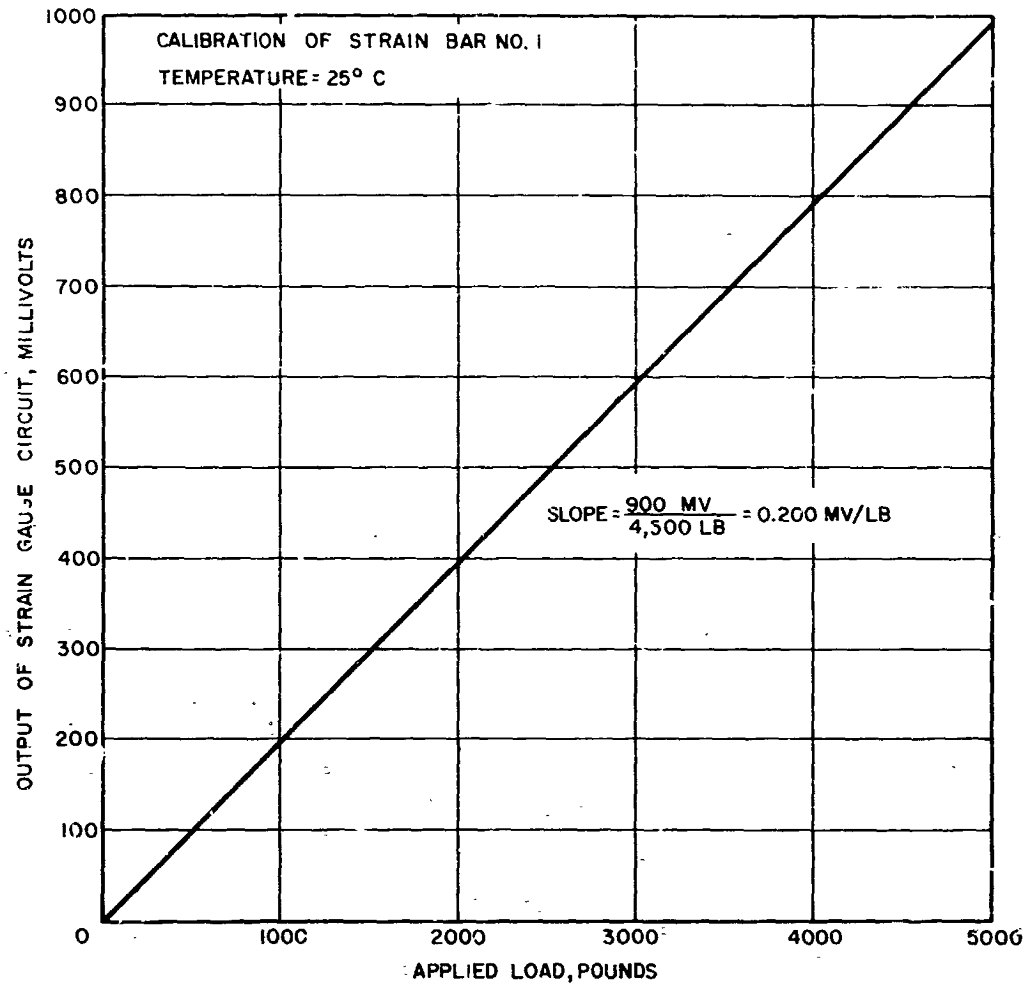
1. D. Horwitz designed the equipment modification to accomodate the mechanism for dynamic motion.
2. C. F. Seck designed the dynamic drive mechanism.
3. H. E. Davies performed the testing operations.

APPENDIXES

APPENDIX A
CALIBRATION OF LOAD CELL



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APPENDIX B
CHEMICAL COMPOSITION OF TEST MATERIALS

Element \ Material	2014-Al	304 Steel	A 286 Steel	Ti-6Al -4V	Rene' 41	Copper
	Percent					
Copper	4.4	0.11	0.08	-	-	Balance
Iron	0.55	Balance	Balance	0.19	0.15	-
Silicon	0.92	0.44	0.61	-	0.03	-
Manganese	0.70	1.13	1.39	-	-	-
Magnesium	0.45	-	-	-	-	0.001
Zinc	0.12	-	-	-	-	-
Nickel	<0.03	8.3	24.5	-	Balance	-
Chromium	0.028	18.2	15.5	-	18.5	-
Titanium	0.036	-	1.96	Balance	3.0	-
Molybdenum	-	0.38	1.20	-	10.0	-
Carbon	-	0.06	0.05	-	0.05	-
Vanadium	-	-	0.38	4.3	-	-
Aluminum	-	-	0.32	6.2	1.4	-
Hydrogen	-	-	-	0.052	-	-
Silver	-	-	-	-	-	0.004